TNO-report

TM-96-B011

TNO Human Factors
Research Institute

Kampweg 5
P.O. Box 23
3769 ZG Soesterberg
The Netherlands

Phone +31 346 35 62 11
Fax +31 346 35 39 77

title

Evidence for a multi-stage model of practice in sequential movement tasks
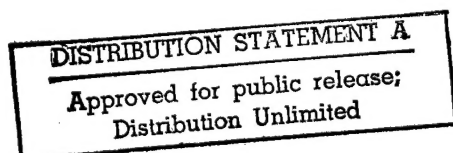
6

author
W.B. Verwey

date
1 August 1996

In case this report was drafted on
instructions, the rights and obligations of
contracting parties are subject to either the
Standard Conditions for research
instructions given to TNO, or the relevant
agreement concluded between the
contracting parties.
Submitting the report for inspection to
parties who have a direct interest is
permitted.

number of pages   :   45   (incl. appendices,
                                  excl. distribution list)

19970212 013

DTIC QUALITY INSPECTED 3

Managementuittreksel   TNO Technische Menskunde, Soesterberg

titel   : Evidence for a multi-stage model of practice in sequential movement tasks
                 (Evidentie voor een multi-stadium model voor oefening in een sequentiële bewe-
                 gingstaak)
auteur   : Dr. W.B. Verwey
datum   : 1 augustus 1996
opdrachtnr.   : B95-008
IWP-nr.   : 788.2
rapportnr.   : TM-96-B011

Het doel van deze studie was de effecten van oefening vast te stellen in een taak waarin vaste bewegingspatronen worden geproduceerd. Eerder onderzoek liet zien dat zich een geïntegreerde representatie, een motor-chunk, ontwikkelt bij herhaalde uitvoering van eenzelfde bewegingspatroon. De motor-chunk zou gebruikt worden om het bewegingspatroon te sturen op het niveau van een verwerkingstadium genaamd "sequentie constructie". Dit zou eerdere verwerkingstadia ontlasten en daarmee de weg openen voor gelijktijdige verwerking van informatie op verschillende niveaus. De huidige studie zocht aanwijzingen voor het sequentie constructie stadium en het idee dat het effect van oefening op dit stadium (i.e., de ontwikkeling van motor-chunks) los staat van oefeneffecten op het respons selectie stadium. Het gerapporteerde experiment omvat een oefenfase met 2500 trials en vier transfer fases. Onafhankelijkheid van respons selectie en sequentie constructie werd aangegeven door de effecten van de consistentie van stimulus-op-sequentie mapping, voorperiode duur, en de lengte van de bewegingssequenties. De transferfases laten verdere evidentie zien voor onafhankelijke effecten van oefening op respons selectie en sequentie constructie en voor gelijktijdige verwerking van informatie op verschillende niveaus van verwerking.

CONTENTS

Report No.:	TM-96-B011
Title:	Evidence for a multi-stage model of practice in sequential movement tasks
Author:	Dr. W.B. Verwey
Institute:	TNO Human Factors Research Institute Group: Skilled Behavior
Date:	August 1996
DO Assignment No.:	B95-008
No. in Program of Work:	788.2

SUMMARY

The purpose of the present study was to explore the effects of practice in a task in which fixed movement patterns are produced. Earlier studies indicated that an encapsulated representation, a motor chunk, develops when a certain movement pattern is repeatedly executed. The motor chunk would be used to control the production of the movement sequence at a processing stage called sequence construction. This would free processing capacity at earlier processing stages and allow for concurrent processing. The present study sought evidence for the sequence construction stage and the notion that the effect of practice at this stage (i.e. motor chunks development) is independent from that at the response selection stage. The reported experiment included a 2500 trial practice phase and four transfer phases including serial response production, stimulus-response reversal, and production of familiar sequences in rapid succession. In the practice phase, independence of response selection and sequence construction was indicated by effects of mapping consistency, foreperiod duration, and sequence length. The transfer phases showed further evidence for independent effects of practice at response selection and sequence construction as well as for concurrent processing.

Evidentie voor een multi-stadium model voor oefening in een sequentiële bewegingstaak

W.B. Verwey

SAMENVATTING

Het doel van deze studie was de effecten van oefening vast te stellen in een taak waarin vaste bewegingspatronen worden geproduceerd. Eerder onderzoek liet zien dat zich een geïntegreerde representatie, een motor-chunk, ontwikkelt bij herhaalde uitvoering van eenzelfde bewegingspatroon. De motor-chunk zou gebruikt worden om het bewegings-patroon te sturen op het niveau van een verwerkingstadium genaamd "sequentie con-structie". Dit zou eerdere verwerkingstadia ontlasten en daarmee de weg openen voor gelijktijdige verwerking van informatie op verschillende niveaus. De huidige studie zocht aanwijzingen voor het sequentie constructie stadium en het idee dat het effect van oefening op dit stadium (i.e., de ontwikkeling van motor-chunks) los staat van oefeneffecten op het respons selectie stadium. Het gerapporteerde experiment omvat een oefenfase met 2500 trials en vier transfer fases. Onafhankelijkheid van respons selectie en sequentie constructie werd aangegeven door de effecten van de consistentie van stimulus-op-sequentie mapping, voorperiode duur, en de lengte van de bewegingssequenties. De transferfases laten verdere evidentie zien voor onafhankelijke effecten van oefening op respons selectie en sequentie constructie en voor gelijktijdige verwerking van informatie op verschillende niveaus van verwerking.

1   INTRODUCTION

There are various models of skill development in perceptual-motor tasks. One type of model focusses on practice effects in tasks in which the major skill of the performer lies in the rapid *selection* of a response. There is ample evidence that practice reduces the time to select a response considerably (e.g., Logan, 1979, 1988; Mowbray & Rhoades, 1959; Proctor & Dutta, 1993). For instance, while response times usually increase with a larger set of alternative responses, this set size effect disappears with practice. This finding is generally explained by the notion that practice yields associations between stimulus (or stimulus category) representations and response representations (e.g., Logan, 1988; Pashler & Baylis, 1991; Schneider, 1985) as if response selection practically bypassed.

Several researchers stated that practice effects in speeded choice tasks have their primary locus in response selection (e.g., Welford, 1976; Pashler & Baylis, 1991; Teichner & Krebs, 1974). This is understandable in the light of the simple nature of the responses used in their studies. Yet, it is not likely that it also holds for tasks in which relatively complex movement patterns are carried out. Models of movement production stress the importance of practice in the execution of movement patterns. One need only think of skills like speech, drawing, and writing to realize that practice has a tremendous effect on the proficiency with which more complex movement patterns are being produced (e.g., Grudin, 1983; Haggard, 1991; Thomassen & Van Galen, 1992; Van Galen, 1991). Recently, Verwey (1994b, 1996) advanced the notion that practice integrates representations of individual movement elements into a single representation, a *motor chunk*, which can be selected as a whole and which controls the execution of an entire movement pattern. In writing, for instance, there would be motor chunks for each individual letter (Thomassen & Van Galen, 1992). The notion that practice has separate effects on different processing stages is in line with the more general idea that, with practice, performance gains from the presence of consistent task components even if the total task is not consistent (e.g., Fisk, Oransky & Skedsvoldy, 1988; Fisk & Schneider, 1984).

The view that selecting responses and executing movement sequences are separable suggests that these can be practiced in isolation. It is also closely related to the traditional idea that information is processed in a series of discrete and independent processing stages (Sternberg, 1969). Independence of processing stages is demonstrated by additive effects on reaction time of variables affecting different stages. Recently, Sanders (1990) reviewed two decades of research with this additive factor method. He presented evidence for a model with seven independent processing stages for choice reaction tasks. Recently, the notion that processing involves independent processing stages has regained attention of various researchers who report evidence that information can be processed simultaneously at different processing stages. For example, perceptual processing can overlap with selecting and executing earlier responses (e.g., Levy & Pashler, 1995; Pashler, 1989, 1994). Concurrent processing at independent stages is probably also used when movement sequences are generated (Verwey, 1996; Verwey & Dronkert, 1996). However, the production of movement patterns has been investigated little within the additive factors tradition.

Since the early sixties, it has been known that sequences of a limited number of individual movements can be prepared by loading representations of the individual movements into a short term motor buffer (Henry & Rogers, 1960). Verwey (1994b) called this stage sequence construction. Sequence construction would follow the response selection stage and precede stages responsible for executing the content of the motor buffer. The possibility to use sequence construction to control movement sequences would make processing capacity at earlier stages available for concurrent processing of information. This would, for example, enable concurrent preparation of forthcoming movement sequences.

Empirical evidence for this contention was not presented. Because sequence construction is responsible for loading the motor buffer, it would cause the typical effect that longer sequences are initiated more slowly than shorter ones, that is, the complexity effect. In line with the notion that the selection of an (integrated complex or elementary) response and the preparation of a movement pattern movement are carried out at different processing stages, Verwey (1995, 1996) argued that practice should have separable effects on response selection and sequence construction. Practice effects on response selection would be evidenced by a reduction of set size effects and slowed selection if familiar stimulus-response mapping are changed. Sequence construction would gradually speed up with practice because buffer loading involves loading integrated sequence representations, that is, motor chunks, into the motor buffer in a single step. This would be the reason that the complexity effect reduces considerably with practice (Canic & Franks, 1989; Van Mier & Hulstijn, 1993; Verwey, 1994a) and that little transfer is found of practice with one movement sequence to the production of modified sequences (Verwey, 1996).

If response selection and sequence construction are independent processing stages, variables affecting one stage should not affect the other stage (Sternberg, 1969) and practice should have different and separable effects on either stage. Moreover, the processing stages that are responsible for producing each individual movement on basis of the motor buffer content should not be affected by variables affecting response selection and sequence construction.

There are some indications supporting independence of response selection and sequence construction. Inhoff, Rosenbaum, Gordon and Campbell (1984) observed that the effect of stimulus-response compatibility, which is a typical response selection effect, was independent of the complexity effect, which would be caused by sequence construction. Moreover, an unpublished study showed that when stimulus-response mapping was reversed, response time increased considerably while the size of the complexity effect and sequence execution rate did not change (Verwey, 1992). However, evidence in favor of independence of response selection, sequence construction and sequence execution is scarce. Besides, evidence for motor chunks comes from a cycling keypressing task but whether motor chunks also develop when a limited number of movement sequences is practiced in a choice reaction time task remains to be proven.

In short, there is reason to believe that independent processing stages are responsible for selecting responses, for constructing movement sequences, and for executing the motor buffer content, and that practice has independent effects at these stages. That is, a proper model of practice in perceptual-motor tasks should be a multi-stage model of practice. Yet,

evidence for this notion is limited. In this study, effects of practice on the selection, construction, and production of movement sequences are investigated in order to show that practice effects consist of different components. An experiment is described which included a practice phase and four transfer phases. The same group of participants joined in all phases and carried out various sequential keypressing tasks. The practice phase involved about 2500 practice trials, 500 for each of five keypressing sequences. Independence of response selection and sequence construction was examined by manipulation of the consistency across practice of stimulus-to-sequence mappings and of sequence length. Foreperiod duration was varied to examine whether response selection and sequence construction can be prepared in advance of sequence initiation. The first transfer phase tested whether the motor chunks that had developed with practice can also be used in a serial response task which probably requires representations at the response selection level. Transfer phase 2 addressed whether the selection of the practiced sequences would be more sensitive to the absence of preparation after varied than after consistent mapping. The third transfer phase addressed the effects of reversing the stimulus-to-sequence mapping for two consistently mapped sequences while retaining the mapping of the third consistently mapped sequence. Finally, transfer phase 4 examined whether selection and execution of movement sequences concur when two familiar sequences are produced in rapid succession. The effect of these manipulations on sequence execution rate was evaluated in all phases.

2   PRACTICE PHASE

A main purpose of the practice phase was familiarizing participants with the selection and production of different keypressing sequences in a five-choice reaction time (RT) task. However, the practice phase also allowed a first test of the notion that response selection and sequence construction are independent processing stages which are both affected by practice.

According to practice models of response selection (e.g., Logan, 1979; Pashler & Baylis, 1991), consistent practice of stimulus-to-response mappings leads to more rapid selection of the appropriate response when compared with varied mappings. Sequence production models assume that repeated execution of the same movement sequence invokes the development of motor chunks. This greatly reduces the time required for loading the motor buffer at the sequence construction stage which is indicated by a reduction of the complexity effect with practice (Canic & Franks, 1989; Hulstijn & Van Galen, 1983, 1988; Van Mier & Hulstijn, 1993; Verwey, 1994a). These effects of mapping consistency and sequence length with practice are not new but it is unclear whether they are independent (i.e., additive) as suggested by an additive factor model. Besides, if sequence execution is indeed independent of response selection, sequence production rate should be unaffected by mapping consistency.

A related issue concerns the moment that response selection and sequence construction are carried out. There are some indications that response selection can be carried out some time before the response is to be carried out so that a foreperiod between the imperative stimulus and a go-signal changes a choice RT task into a simple RT task. For example, the typical

word frequency effect that is found on RT (Shaffer, 1973; Rosenbaum, 1991) and would indicate a response selection effect (Verwey, 1994b) disappears in simple RT (Sternberg *et al.*, 1978). Another case in point is that choice and simple RT become nearly identical with long precue-to-stimulus intervals (Gottsdanker & Shragg, 1985). Indeed, Gottsdanker and Shragg (1985) argued that responses can be selected in advance of the go-signal. Hence, the response selection effects of mapping consistency should affect RT only without foreperiod and not when the imperative stimulus is followed by a foreperiod.

It is less clear whether sequence construction can be carried out long before sequence initiation. In fact, this issue is closely related to a debate between two groups of researchers in the late seventies and early eighties. One group assumed that programming of a complex movement pattern takes place directly in advance of sequence initiation because it induces an exceedingly high state of readiness to respond (Henry, 1980; Marteniuk & MacKenzie, 1980; Sternberg *et al.*, 1978). After a motor program is loaded, it would be difficult to keep from executing the program immediately. These researchers inferred that simple RT is most appropriate for the investigation of programming. This position was later corroborated by Canic and Franks's (1989) observation that the complexity effect was not entirely abolished with extensive practice and a fixed foreperiod. So, even when participants knew exactly when which sequence would have to be produced, motor buffer loading started only after onset of the go-signal.

Other researchers, however, pointed to observations that the complexity effect was not always observed in simple RT tasks and that programming would precede the go-signal in simple RT tasks (e.g., Klapp, 1977; Klapp *et al.*, 1979). Recently, Verwey (1994b) suggested that the complexity effect in choice RT tasks could be caused by two independent processing stages. One was sequence construction which might precede the go-signal in simple RT tasks. The other stage was the retrieval stage (Sternberg *et al.*, 1978) which is responsible for searching each individual sequence element in the motor buffer. This stage would precede execution of each sequence element, including the first, and cause the complexity effect in simple RT and part of the complexity effect in choice RT. If sequence construction can indeed be carried out before onset of the go-signal, the complexity effect should be smaller with than without a foreperiod that separates the imperative, choice stimulus and a go-signal. In contrast, if construction of the sequence in the motor buffer necessitates immediate execution and, hence, sequence construction always takes place after onset of the go-signal, the complexity effect should not be affected by the presence or absence of a foreperiod. Notice that if the complexity effect is not affected by the foreperiod while the consistency effect is, this will also prove that response selection precedes sequence construction.

In short, the practice phase tested the notion that the response selection and sequence construction stages show independent effects of practice. Consistent stimulus-to-sequence mappings should show faster sequence initiation than varied mappings because response selection is faster after consistent than after varied mapping. This effect should be unaffected by sequence length and its expected reduction with practice as these effects would originate at the sequence construction stage. To examine whether response selection and sequence construction can precede sequence initiation without actually executing the sequence, a 2.5 s

foreperiod was introduced for half of the participants between onset of the imperative stimulus and onset of a key specific cue which acted as go-signal. On the assumption that response selection can be carried out during this foreperiod, it is expected that mapping consistency will not affect RT for this group of participants. If sequence construction can be carried out during the foreperiod the complexity effect should be considerably smaller with than without foreperiod. Finally, because sequence execution is carried out by processes independent of response selection and sequence construction, neither mapping consistency nor foreperiod duration should affect sequence execution.

2.1 Method

Task

Participants positioned the left little, ring, middle, and index finger on the z, d, f, g keys of a PC keyboard and the right thumb, index, middle, ring, and little finger on the space bar, and on the j, k, l, and / keys, respectively. These assignments were chosen so that each finger could easily press a separate key. The computer screen displayed bright blue outlines of nine squares on a black background in the same spatial arrangement as the assigned keys. A key was depressed when the area enclosed by one of the nine squares became homogeneously green as if a light had been turned on. Immediately after depression of the associated key the content of the square became black again as if the light had been turned off. It was allowed to release a key after the ensuing one had been depressed.

Each participant practiced five different sequences; three 2-key sequences and two 6-key sequences. Basically, the same sequences were used for all participants. However, to prevent response times from being affected by finger-specific effects the keys used in each sequence were shifted one key for each next participant according to the basic series z d f g j k l / [space] while [space] was followed again by z. For example, when Participant 1 executed the sequence g l z / [space] k, Participant 2 depressed j / d [space] z l, and Participant 3 depressed k [space] f z d /. Given that nine keys were involved, Participant 10 had the same sequences as Participant 1, etc. This procedure allowed the development of an integrated memory representation for each of the five sequences while, across all participants, each reaction and each interkey time was based on pressing all nine keys.

Each trial started with presentation of the *imperative* stimulus. Half of the participants, the *preparation* group, had a Stimulus Onset Asynchrony (SOA) between imperative stimulus and onset of the first key specific square of 2.5 s whereas the other half, the *immediate* group, had a SOA of 0 s. All participants were instructed to take note of the imperative stimulus and were warned that, later, they would have to produce the sequences on the basis of the imperative stimulus alone. The same set of five stimuli was used with all participants. This set involved the digits 2 to 6. Stimuli were balanced across sequences for the individual participants: whereas Participant 1 gave 2-key sequences in response to the stimuli 2, 4, and 6, Participant 2 gave these sequences to 3, 5, and 2 and Participant 3 to 4, 6, and 3.

As indicated in the two examples in Table I, two out of the five stimulus-sequence mappings were alternated in each successive practice block. These mappings are termed varied mapping. The other three mappings remained fixed during practice and are referred to as consistent mapping. For all participants the varied mapping sequences involved a 2- and a 6-key sequence.

Table I Examples of the assignment of keys to imperative stimuli. Across all participants, keys were balanced over fingers and imperative stimuli were balanced overs sequences.

	imperative stimulus	keying sequence	mapping
participant 1	2	l [space]	consistent
	3	g l z / [space] k	consistent
	4/5	f j	varied
	5/4	/ d j f g z	varied
	6	d k	consistent
participant 2	6	/ z	consistent
	2	j / d [space] z l	consistent
	3/4	g k	varied
	4/3	f k g j d	varied
	5	f l	consistent

Procedure

Upon arrival at the institute, participants were introduced to the experiment and their task in the practice phase. It was indicated that on the basis of their performance on each block of trials they would receive a score and that the best six out of 18 participants would earn a bonus. After the first two sessions the experimenter urged participants to take note of the imperative stimulus, and not only respond to the key specific cues, because they would later have to produce the sequences on the basis of that stimulus alone.

Each participant carried out six practice sessions on Day 1, seven on Day 2, and two on Day 3. The Day 3 practice sessions were followed by the transfer sessions on Day 3 and 4 described later in this paper. In the first week, fourteen participants participated in the experiment. They were divided into two groups of seven participants. Participants in one group belonged to the preparation group while the others belonged to the immediate group. While each participant of one group performed the experimental task on a computer in seven isolated rooms, the participants of the other group relaxed in an adjacent room. After each session the two groups changed places. This resulted in a rest and test schedule of 15 to 20 min. After these participants had finished the experiment, this procedure was repeated in the second week with six participants (two participants who participated in the first week, performed poorly and were replaced by two participants in the second week).

Practice sessions consisted of two 84 trial blocks with a 22 s break in between. Each block was followed by a performance score which ranged from 0 to 100 points. The scored consisted of a weighed combination of speed and accuracy. Given that performance improvement obeys a power law (Newell & Rosenbloom, 1981) the score was determined with a logarithmic function so that late in practice a relatively small improvement still yielded a perceivable score increase.

Accuracy affected scoring in that high error rates were punished by reducing the score: each additional error percentage equalled 20 ms slower responding. To prevent cautious and therefore slow keypressing, error rates of less than three percent evoked the instructions to increase keying speed - unless the average response time per key was below 150 ms. Below three percent errors, the error rate was artificially increased before the performance score was calculated by twice the difference between the actual error percentage and three percent. Hence, with three percent errors the time-based score was reduced least. Participants were not informed of this procedure. Performance scores in terms of response times and accuracy were not given.

Apparatus

The experiment was conducted on seven identical IBM AT compatible (80386) computers with NEC Multisync VGA 3D color monitors. Stimulus presentation and response registration were controlled through Micro Experimental Laboratory software (MEL version 1.0; Schneider, 1988). This software package is specially developed for running PC-based experiments. At a typical viewing distance of about 65 cm a square subtended a visual angle of approximately 1°. The stimuli consisted of a bright green area filling the outline of a bright blue square on a black background and were viewed under normal room illumination. The response keys were part of a normal AT-like keyboard (BTC). Although MEL can measure times with 1 ms precision by reprogramming the internal timer, variances caused by keyboard delays were found to add approximately 19 ms to the error variance which, given the large number of trials in the present study, is considered acceptable (Segalowitz & Graves, 1990).

Participants were simultaneously tested in seven sound-attenuated 2.4 × 2.5 × 2 m rooms. There they sat in front of a table on which the keyboard and a computer monitor were positioned. They were monitored by the experimenter through a closed video circuit.

Participants

Participants in this and all later phases of this study were 18 paid students (12 males and 6 females) from the University of Utrecht. They were paid 240 Dutch guilders for participation. Three participants in each group received a bonus of 25 guilders. Two participants of the preparation group were replaced because, at the three final sessions in the practice phase, their speed was relatively low while their error percentages still exceeded 10 percent.

Design

The time between onset of the square and depression of the corresponding key were designated T_1-T_6[1]. T_1—i.e., the reaction time or RT—was analyzed with a Foreperiod (2.5 versus 0 s) × Consistency (consistent mapping versus varied mapping) × Sequence Length (2 versus 6) × Session (15) design with foreperiod as between-participants factor. T_2 in the 2-key sequences was analyzed with a Foreperiod (2) × Consistency (2) × Session (15) factorial design while analyses of the interkey intervals in the 6-key sequences involved a Foreperiod (2) × Consistency (2) × Key Position (5) × Session (15) design. Sequences involving an error were discarded from these analyses. The first four trials of each block were considered warming-up and also discarded.

In order to obtain independence of means and variances, arcsine transformations were carried out on mean error rates per cell before the data were subjected to ANOVAs (Winer, Brown & Michels, 1991). Only the error that occurred first in a sequence was included in the error analyses; later errors were ignored.

2.2   Results

In general, analyses of variance (ANOVAs) were carried out on mean response times per session, condition, participant, and location of the keypress in the sequence. Only errorless trials were included in the response time analyses. Because two sequences were equal with regard to length and consistency—i.e., the 2-key sequences with consistent mappings—a first analysis concerned whether the results associated with these two sequences could be collapsed in further analyses. Planned comparison showed that T_1 (i.e., RT) as well as T_2 did not differ significantly [T_1: 427 versus 440 ms, $F(1,15)=0.17$; T_2: 113 versus 119 ms: $F(1,15)=0.20$, $ps > .20$]. This confirmed that in further analyses the results of the two 2-key sequences in the consistent mapping condition could be pooled.

Session had a main effect on T_1 in the analysis on Sessions 1 to 15 [$F(14,210)=41.9$, $p < .001$]. This session effect was stronger in the condition with foreperiod [$F(14,210)=2.3$, $p < .01$] but this group difference could be attributed to Session 1 only because it was not significant in an analysis on Sessions 2-15 [$F(13,195)=1.2$, $p > .20$]. Hence, improvement in Sessions 1 and 2 was greater with than without foreperiod. In later sessions it was comparable.

The ANOVA on T_1 showed that consistency had a significant main effect [consistent mapping: 446 ms, varied mapping: 465 ms; $F(1,15)=7.8$, $p < .02$] and that the consistency effect differed as a function of foreperiod [$F(1,15)=5.6$, $p < .04$; Figure 1]. Planned comparisons confirmed that the consistency effect was significant without foreperiod [$F(1,5)=14.1$, $p < .01$] and not significant with foreperiod [$F(1,15)=0.9$, $p > .20$]. Practice

---

[1] In later phases of this paper, RT will be used to indicate the time between onset of the imperative stimulus (i.e. the digit) and the first keypress. To emphasize that the Preparatory group responded to the first key-specific cue rather than to the imperative stimulus, T_1 will be used in this phase instead.

did not affect the size of the consistency effect [$F(14,210)=0.9$, $p>.20$]. Planned comparisons in the condition without foreperiod showed that the consistency effect remained significant across practice [Sessions 1-5: 533 versus 560 ms, $F(1,15)=8.2$, $p<.01$; Sessions 10-15: 391 versus 407 ms, $F(1,15)=20.8$, $p<.001$].
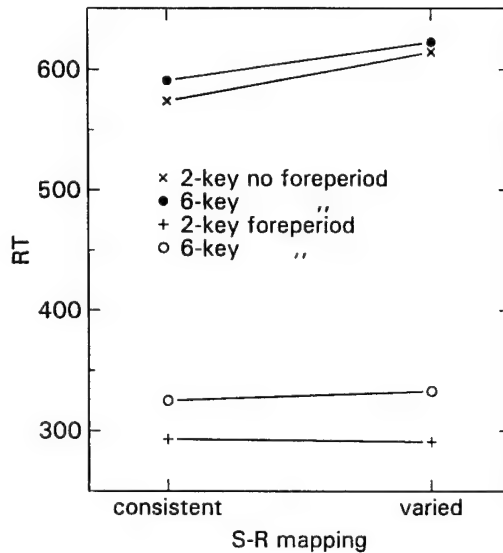

Fig. 1 T_1 as a function of foreperiod and mapping consistency across Session 1−15.

Across all sessions, the complexity effect (difference in T_1 between 2-key and 6-key sequences) amounted to $(468-443=)$ 25 ms and was marginally significant [$F(1,15)=3.9$, $p=.07$]. The sequence length × session interaction showed that the complexity effect reduced with practice [$F(14,210)=3.2$, $p<.001$] which was confirmed by planned comparisons in Sessions 1−5 [46 ms; $F(1,15)=6.9$, $p<.05$] and Sessions 10−15 [10 ms; $F(1,15)=1.0$, $p>.20$].

The size of the complexity effect was affected neither by mapping consistency nor by foreperiod [$F(1,15)=0.9$; $F(1,15)=1.0$, resp., $ps>.20$]. On the average, the complexity effect was even greater with than without foreperiod (Fig. 1). A separate analysis on the condition without foreperiod showed no significant interaction between consistency and sequence length [$F(1,8)=0.02$, $p>.20$]. The consistency × sequence length interaction did not reach significance in the sessions with the largest complexity effect either [Sessions 2−5; $F(1,8)=0.01$; $p>.20$; complexity effect: 41 ms]. This shows that he complexity effect and the consistency effect were independent.

Consistency did not effect interkey intervals [2-key sequence: $F(1,15)=1.2$; 6-key: $F(1,15)=1.5$, $ps>.20$]. Foreperiod did not have a significant effect on interkey intervals in 6-key sequences [$F(1,15)=2.1$, $p>.17$] but in 2-key sequences, T_2 was longer without than with foreperiod [147 versus 96 ms; $F(1,15)=4.7$, $p<.05$]. This suggests that without foreperiod the 2-key sequence was not carried out as a whole. However, the size of the T_2 lengthening reduced with practice [$F(14,210)=2.8$, $p<.001$] from $(231-151=)$ 80 ms in Sessions 1−5

to $(97-64=)$ 33 ms in Sessions $11-15$. In Session $11-15$, the difference no longer reached significance $[F(1,15)=3.0, p>.10]$.

Finally, the ANOVA on arcsine transformed error scores of 6-key sequences in Sessions 2, 3 and 14, and 15 showed main effects of key $[F(5,80)=12.0, p<.001]$ and a Key $\times$ Session interaction $[F(15,240)=5.9, p<.001]$. This interaction indicated that while error percentages across positions ranged between 1 and 4 in Sessions 2 and 3 in a unspecific way, Sessions 14 and 15 showed a clear pattern in that percentages increased with position until Position 5 where it dropped again (0.9%, 2.7%, 5.3%, 6.0%, 6.3%, and 2.0%, resp.).

2.3   Discussion

The results corroborate that response selection and sequence construction are independent processing stages which are both subject to practice. Furthermore, when sequence initiation was preceded by a foreperiod, responses were selected in advance of the go-signal but the construction of the sequences started directly before sequence initiation. Finally, response selection and sequence execution stages proved independent.

In the condition without foreperiod, consistent mappings resulted in faster sequence initiation than varied mappings. This consistency effect was observed in all sessions and did not reduce with practice. It is in line with associations between stimulus and response representations after consistent mapping practice which facilitate the selection of responses. The fact that, in the condition with foreperiod, consistency did not affect T_1 confirms that response selection took place before onset of the first key specific cue.

The complexity effect was indicated by faster initiation of 6-key sequences as compared with 2-key sequences. The complexity effect reduced with practice suggesting that motor chunks developed. Chunk development was also demonstrated by the development of a fixed error pattern across sequences in later sessions. In the condition without foreperiod the second key of the 2-key sequence was slower than in the foreperiod condition but this foreperiod effect also diminished with practice. Apparently, the 2-key sequence was executed as a whole only after considerable practice unless advance preparation was possible (cf. Verwey, 1996). This is not surprising as the gain from performing 2-key sequences as a whole is not so big as with 6-key sequences. However, eventually motor chunks were used for 2-key sequences too.

The size of the complexity effect was not significantly affected by foreperiod and it was even somewhat greater with than without foreperiod. This corroborates that sequence construction always took place after onset of the first key specific cue. It suggests that constructing the sequence in the motor buffer—or at more proficient skill levels: loading a motor chunk—necessitates immediate execution (Canic & Franks, 1989). This finding rejects the notion that the complexity effect in simple RT tasks is caused only by a retrieval stage at which the motor buffer is searched for individual elements, and not by sequence construction (Verwey, 1994b). In that case, the complexity effect would have been smaller in the presence of a foreperiod which is virtually a simple RT condition.

Even though it is important to see that consistency and sequence length had statistically significant effects, a more important result is that these effects did not interact in the condition without foreperiod. In other words, the complexity effect was additive to the effect of mapping consistency indicating independence between response selection and sequence construction. Additional evidence for independence of both processing stages comes from the observation that occurrence of the consistency effect depended on foreperiod whereas foreperiod did not affect the size of the complexity effect. Hence, response selection was carried out during the foreperiod whereas sequence construction was postponed until the moment sequence production could start. This is in line with Canic and Franks's (1989) claim that the buffer content is subject to rapid decay and indicates that the complexity effect is not different in choice and simple RT tasks; hence, simple and choice RT can both be used for investigating motor programming in sequence production tasks. Besides, simple RT tasks have the advantage that response selection effects are excluded.

In the introduction, it was claimed that if processing stages are indeed independent these should also be separately and independently affected by practice. So, T_1 should decrease more rapidly when one stage than when two stages have an effect. The present results confirm this. In the presence of a foreperiod when response selection probably preceded T_1, T_1 reduced more rapidly than without foreperiod when response selection occurred during T_1. Examination of the data showed that this effect was mainly present at Day 1.

Finally, sequence execution rate was not affected by mapping consistency which is in line with the notion that response selection and sequence execution are carried out at independent processing stages too. The effect of foreperiod on the second keypress of the 2-key sequences suggests that short sequences are initially produced as individual actions (i.e., separately selected at the response selection stage) but slowing of the second keypress diminished with practice.

In summary, the findings are in line with the notion that consistent stimulus-to-sequence mappings induce the development of associations between stimulus and sequence specific representations. With practice, sequence construction seems facilitated by the possibility to load motor chunks from long term memory into the motor buffer in a single processing step. Selecting a specific movement sequence can be carried out in advance without the need to immediately start execution. In contrast, loading the motor buffer seems to require immediate execution of the sequence and is therefore postponed until after onset of the go-signal. Taken together, these results are in line with the notion that response selection and sequence construction are independent processing stages. Absence of the consistency effect on sequence execution rate is in line with independence between response selection and sequence processing stages.

3   TRANSFER PHASE 1: SERIAL RESPONSE PHASE

A number of researchers have addressed the possibility that movement sequences are learned implicitly, that is, without an intention to learn and even without awareness of the sequence

(e.g., Cohen, Ivry & Keele, 1990; Curran & Keele, 1993; Nissen & Bullemer, 1987). The typical task to investigate implicit learning is the serial response paradigm. In this task, participants respond to a limited set of (e.g., four) stimuli by pressing a key associated with the stimulus position. Each response is followed by the next stimulus, etc. The common finding is that when the sequence follows a fixed pattern, participants gradually perform better than with a random order. When participants are transferred from the repeating sequence to a random sequence, RT increases again (also see Hartman, Knopman & Nissen, 1989; Willingham, Nissen & Bullemer, 1989). Several studies demonstrated that this effect also occurs when participants are not aware of the presence of the non-random part in the sequence (e.g., Lewicki *et al.*, 1987, 1988; Willingham *et al.*, 1989). The general explanation is that some representation develops which, on the basis of previous responses, biases the next response.

One might wonder whether this representation is comparable to the earlier mentioned motor chunks. This is probably not the case. First of all, motor chunks are intentionally loaded in a motor buffer whereas the observation that awareness is not required, implies that the effects of practice in implicit learning does not require advance loading. Furthermore, the motor buffer has a limited capacity of five to seven elements in early practice (Verwey, 1994b) whereas the sequences in the implicit paradigm are often much longer than that. Therefore, it seems likely that in the serial response paradigm, improvement does not rely on motor chunk development (i.e., at the sequence construction stage) but rather on the development of some representation at another processing stage. At this stage, practice effects would rely on (unintentional) priming. A likely candidate for this stage is response selection. So, implicit learning might result in representations at the response selection stage whereas motor chunk development affects sequence construction.

The distinction of sequential learning at two processing stages in this paper parallels several models developed for the serial response paradigm that also distinguished between practice effects at different processing stages. Cohen *et al.* (1990) reported that unique transitions between subsequent events could be learned in the presence of attentional distraction whereas non-unique transitions could not. They argued that sequence learning involves two distinct learning mechanisms. One mechanism forms associations between adjacent items which automatically facilitate movement production. The other mechanism would build a hierarchic code in which ambiguous structures are parsed and higher level description are provided for each part. This parsing process would remain to require attention and awareness.

A similar distinction between different effects of practice in the serial response paradigm can be found in Stadler's (1992) *verbatim* (i.e. deterministic) and *aggregate* (i.e., stochastic) sequence representations (also see Curran & Keele, 1993). It is tempting to assume that the independent stochastic and deterministic effects of practice in the serial response paradigm occur at the response selection and sequence construction stages, respectively. That is, selecting and executing a certain response facilitates selection of other responses, the magnitude of which depends on the number of times each of them used to follow. Facilitation would be based on a priming-like, unintentional mechanism (e.g., Posner & Snyder, 1975). On the other hand, the movement elements in a fixed sequence are controlled by a

motor chunk which is intentionally loaded into the motor buffer at the sequence construction stage.

If the distinction is correct, one might argue that the existence of a sequence representation at one stage (e.g., at the sequence construction stage) should not affect performance when the representation at the other stage (e.g., response selection) is required. This prediction contrasts with models of practice that do not distinguish between representations at different processing stages (Logan, 1988; Newell & Rosenbloom, 1981) and which predict that sequence production performance gains considerably from the occurrence of familiar sequences, irrespective of the way in which they were learned.

The aim of the present phase was to test the notion that the effects of the practice phase do not facilitate performance of the same sequences in the serial response paradigm. The reason would be that task performance in the serial response paradigm relies on another type of representation than the one that developed when producing fixed movement patterns. Cohen *et al.* (1990; Experiment 1) used 200 repetitions of a certain response sequence, and Stadler (1992) 168 repetitions of the same sequence for obtaining evidence for learning in serial responding. The present practice phase had incorporated about 500 repetitions of each sequence. According to the results of the practice phase and also those of transfer phases reported later, this did not induce motor chunk development. Therefore, if the same representations underlie performance in discrete sequence production and serial responding then the amount of practice in the practice phase should be enough for obtaining considerable transfer of training to the serial response task.

3.1   Method

Task

The task in this phase was similar to that in the practice phase in the sense that participants had their fingers on the same keys and the same set of nine squares was presented at the screen. However, they were now instructed to respond as quickly as possible when a square "switched on" and they were told that there would be no specific order in which this occurred. Care was taken that a key was not immediately repeated. In the first session of this phase, the practice session, familiar sequences did not occur but in the second session, the experimental session, a familiar sequence started at each tenth keypress. As soon as this sequence was completed, random keys followed again until the next tenth keypress when a next familiar sequence followed. In case the first keypress of a familiar sequence had coincidentally just been given as random key press, this was recognized by the software and the sequence proceeded with the second keypress in the sequence instead of the first.

Procedure, Apparatus and Participants

Before the beginning of the practice session, participants were instructed about the serial response task. They were told to respond as rapidly as possible to each key-specific cue without making many errors. The square remained "on" as long as the correct key had not

yet been pressed. Errors were indicated by a message that the wrong key had been pressed. Only after the correct key was pressed was the square was switched "off".

As the practiced sequences were mapped to different fingers for different participants, care was taken that in the experimental session each participant had his or her own familiar sequences. Each session consisted of four blocks, each consisting of 350 trials and lasting about 5 min. Pauses occurred only between blocks. As in the practice phase, each block was followed by a score and, in case of error rates over six percent, a message that the participant should make less errors. After completing the experimental (i.e., second) session, each individual participant was first asked whether he or she had noticed anything special. Irrespective of the answer they were next asked whether they had noted that some familiar sequences had occurred. If they responded affirmative they were asked how often they thought these sequences had occurred and whether they had used that knowledge in performing the serial response task.

The same equipment was used as in the practice phase and the task was performed by the same participants in the same sound attenuated rooms.

Design

Given that the spatial distance between two successive keypresses affects the interkey interval (see Results section), the effects of familiar 6-key sequences on interkey intervals were determined by comparing the interkey intervals within those sequences with the intervals between pairs of the same keys that had randomly occurred in isolated situations. The experimental design was a four-way factorial. The factors were the presence of a foreperiod during the practice phase (2 levels), whether the sequence had been practiced with consistent or varied stimulus-response mapping (2), key position (5), and whether the response pair is in the context of a complete 6-key sequence or not (2). Only foreperiod was between-participants, the other ones were within-participants.

With regards to familiar 2-key sequences, the effect of practice was assessed by comparing RTs to the second stimulus of a familiar pair with RT to the second stimulus of unfamiliar pairs with the same spatial distance. To increase statistical power, this analyses also involved familiar pairs that occurred in random parts of the practice session. These data were analyzed by a Foreperiod (2) × Session (2) × Sequence design with foreperiod as only between-participant factor. Sequence had either 3 (Random versus Sequence 1 versus Sequence 3) or 2 levels (Random versus Sequence 5).

3.2 Results

Initial analysis of Session 1 showed that the distance between subsequent keys had a marked effect on interkey intervals and on error rate [$F(7,112)=28.3$, $p<.001$; $F(7,112)=6.0$, $p<.001$, respectively]. The farther away a key from the previous one the slower RT and the more errors (distance ±1: 506 ms, 4.0%; ±2: 529 ms, 5.4%; ±3: 543 ms, 5.7%; ±4: 552 ms, 6.4%). This distance is defined as the number of keys between successive keys plus

one. For example, the distance of the keys "d" and "f" is one (adjacent keys) and the distance between "d" and "k" four. Distances greater than four did not occur because then the distance reduced again as the sequence cycled across participants.

In the experimental session, a main Context effect [$F(1,16)=4.67$, $p<.05$] indicated that, on the average, the intervals within familiar, hidden 6-key sequences were 8 ms shorter than the same intervals that did not occur in the context of a familiar sequence. There was a marginally significant Position $\times$ Context effect indicating that the effect of prior practice was greater for keys at a smaller spatial distances [$F(4,64)=2.3$, $p<.07$; Fig. 2].

The second response of the two familiar, hidden 2-key sequences with a distance of 2 (Sequence 1 and 3) was executed faster than in case of random pairs with the same spatial distance: 508 ms for the familiar sequences and 528 ms for the unfamiliar pairs [$F(1,16)= 3.1$, $p=.09$]. Comparison of the third 2-key sequence with random key orders at the same distance, Sequence 5 (distance 4) did not show an effect of familiarity [550 versus 552 ms; $F(1,16)=0.3$, $p>.20$]. Error analyses yielded no significant effects.
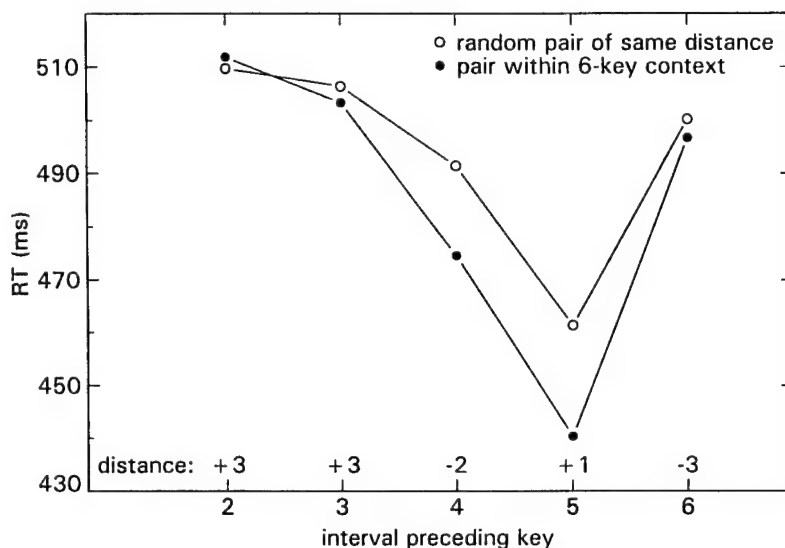

Fig. 2 RT for keypresses within the context of a 6-key sequence and the same pairs in isolated conditions.

After completing the experimental session, four out of 18 participants stated they had sometimes noticed familiar sequences but they indicated not to have used it because sequence execution went too fast. Furthermore, they could not tell how often it had happened. One participant asserted that the familiar sequences had occurred in the practice session too—which was not the case. Hence, awareness of the hidden sequences in the otherwise random serial response paradigm was fairly limited.

3.3 Discussion

This phase examined whether prior practice of discrete movement sequences in the practice phase, affects RT in a continuous serial response task in which these familiar sequences are hidden. The results showed minimal effects of prior practice: on the average, 6-key sequences were executed 8 ms faster than comparable key combinations outside the context of the 6-key sequence and a marginally significant effect of 20 ms was found in two of the three familiar 2-key sequences. These effects are substantially smaller than those found in serial response studies which involved less practice than the present practice phase. For example, Cohen *et al.* (1990) reported effect sizes of over 100 ms for participants who were unaware of a fixed sequence in the serial response paradigm and Curran and Keele (1993) found effects of about 100 ms for participants with little or no awareness of the occurrence of a fixed sequence and effects of about 200 ms for more aware participants.

Awareness of the fact that the earlier practiced fixed sequences occurred in the serial key pressing sequences was very limited. Four out of eighteen participants stated to have some times recognized the familiar sequences but they could not say whether these occurred very often and one of these participants incorrectly maintained that he had noticed the familiar sequences in the practice session too (which consisted of random sequences).

Since awareness is not a prerequisite for the occurrence of effects of implicit learning (e.g., Lewicki *et al.*, 1987, 1988; Willingham *et al.*, 1989) the limited awareness amongst the participants seems not a sufficient explanation for the minor effect of prior practice. However, awareness could have introduced clear performance effects in that participants might have used chunks to finish the familiar sequence. This was not found. The fact that there were still some effects of prior practice can be explained in terms of a multi stage model of practice by the notion that a rudimentary associative representation developed during the earlier sessions of the practice phase at the response selection level. After all, sequence production in early practice also consisted of serially responding to key specific cues just as in the serial response paradigm. Given the evidence for motor chunks development, in the practice phase and in later phases of this paper, it seems more likely that participants switched to integrated sequence production thereby reducing association development at the response selection stage.

Even though these findings can not yet be considered strong evidence, they are certainly in line with the notion that motor chunks do not contribute to serial response speed and, therewith, that different representations underlie skilled sequence production in discrete sequence production and in serial responding. Obviously, as this conclusion is based on the finding of effects of a minor magnitude, further research should provide more solid evidence for the assertion that different representations underlie performance in discrete sequence production and in serial responding. Still, the present data reject the notion that serial behavior relies on associations at one level only (cf. MacKay, 1982; Wickelgren, 1969).

4   TRANSFER PHASE 2: PRESEQUENCE PHASE

As indicated in the introduction, various models assume that practice in a condition with consistent stimulus-to-sequence mappings yields associations between stimulus and response representations which facilitate response selection. This would not occur with varied practice so that stimulus-to-sequence rules would have to be loaded into short-term memory each time anew (e.g., Duncan, 1978; Logan, Zbrodoff & Fostey, 1983; Pashler & Baylis, 1991). Basically, the results of the practice phase are in line with this notion in that consistent stimulus-to-sequence mappings showed faster sequence initiation than varied stimulus-to-sequence mappings. However, in the practice phase the T_1 gain of consistent mapping turned out to be quite small and did not increase with practice. Given that the strength of stimulus-to-sequence mappings would only gradually increase with practice, this is unexpected.

One explanation for the limited size of the consistency effect is that associations developed rapidly, that is, no further practice was required after a single session. It seems unlikely that so little practice is required. It is more probable that response selection in the varied mapping sequences was facilitated with practice by another mechanism that developed with practice. As argued by Logan and others (Logan, 1979, 1980; Logan *et al.*, 1983; Pashler & Baylis, 1991) participants may have been able to develop several sets of stimulus-to-response translation rules for the varied mappings, only one of which was loaded into short term memory prior to each block. This explicit attention to varied mappings might even have resulted in a bias of varied mapping sequences.

If this model is correct, the consistency effect should be bigger when there is no time for advance loading of stimulus-to-response rules. On the other hand, if practice had yielded similar rules for varied and consistent mapping, sequence initiation time should increase to a similar extent for both types of mappings. This notion was tested in Transfer Phase 2 (the presequence phase) by preventing advance rule loading with a serial response task which preceded presentation of the imperative stimuli (i.e., the *presequence*).

Finally, during the entire practice phase, each key press was preceded by a key specific cue. Given the high rates at which sequences were produced in the later practice sessions, it is not likely that participants relied very much on these cues. The availability of motor chunks should have allowed rapid production of the entire key pressing sequence. Still, further evidence is required that, for sequence production, participants relied on internal sequence representations (motor chunks) rather than on specific cues. To test this, key specific cues were removed in this transfer phase. If motor chunks underlie rapid sequence production, performance should not reduce without the key specific cues.

4.1   Method

Participants had their fingers on the same keys and the same set of nine squares was displayed at the screen and the same sequences were produced as in the practice phase. However, there were two major changes. First, each trial started with eight to twelve keypresses in response to onsets of the squares at the screen in a random order, which was

followed by display of one of the five imperative stimuli indicating a practiced sequence. To assure that a firm distinction could be made between square onsets in the random pre sequence and the key-specific cues that had been used before, the squares were filled with a white rather than green content. Second, key specific cues in the familiar sequence were not displayed at all so that participants had to execute the sequence from memory and only on the basis of the imperative stimulus (i.e., the digit). Again, each block was preceded by a message showing stimulus-sequence mappings of consistent mapping and varied mapping sequences. These mappings were the same as those practiced in the practice phase.

This phase included three two-block sessions, each block consisting of 64 trials. Again, blocks were separated by a 22 s break. Performance scores were presented immediately following each block. Sessions 1 and 2 of this phase were performed at Day 3 following transfer phase 1. Session 3 was carried out at Day 4 following an initial practice session which was equal to the original sessions of the practice phase. Notice that there was no distinction between preparation and immediate participants. Any differences found between both groups would have been caused by practice with and without foreperiod in the practice phase.

Participants were instructed orally about this procedure and were told to respond as rapidly as possible without making many errors. Errors in the presequence were indicated by a message that the wrong key had been pressed.

4.2   Results

A Foreperiod (2) × Session (3) × Consistency (2) × Sequence Length (2) ANOVA on T_1 obtained in the three sessions of the present phase showed main effects of session [$F(2,32)$ =73.2, $p<.001$], consistency [1030 versus 1299 ms; $F(1,16)=69.8$, $p<.001$], and sequence length [$1197-1132=65$ ms; $F(1,16)=13.6$, $p<.01$]. The complexity effect indicated by the sequence length effect diminished with practice in this phase [116 ms, 69 ms, and 12 ms in respective sessions, $F(2,32)=7.1$, $p<.01$]. Absence of a significant complexity effect in Session 3 was confirmed by a Tukey HSD post-hoc test on Session 3 alone ($p>.20$). This recurrence and subsequent disappearance of the complexity effect was unaffected by consistency [$F(2,32)=0.3$, $p>.20$]. T_1 was not affected by whether or not participants had had a foreperiod during the practice phase [$F(1,16)=1.1$, $p>.20$].

Comparison of T_1s in the last three practice sessions (Sessions 13-15) and the three sessions of the present transfer phase 2 showed that RT increased considerably in transfer phase 2 [396 versus 1188 ms; $F(1,15)=682$, $p<.001$]. As shown in Fig. 3, the size of the consistency effect increased considerably too [$F(1,15)=63.5$, $p<.001$].
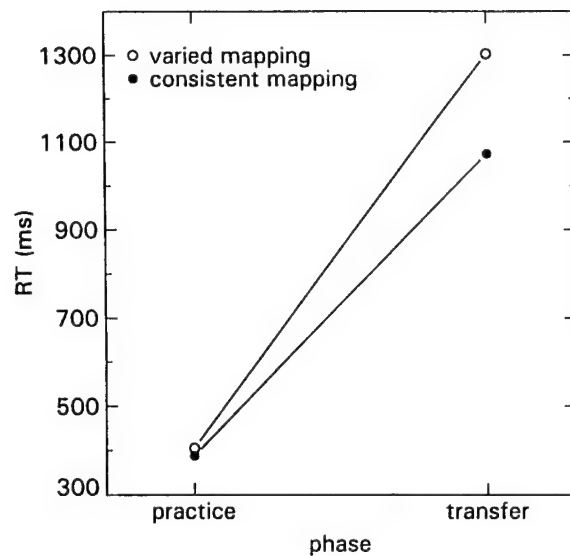
Fig. 3 RT as a function of mapping consistency in the final practice session (Sessions 13–15) and transfer phase 2.

Sequence execution rate of the 2-key sequence (i.e. T_2) was lower in the three transfer sessions than in the last three sessions of the practice phase [Fig. 4: 78 versus 114 ms; $F(1,15)=10.6$, $p<.01$]. Likewise, overall execution rate of the 6-key sequences was generally lower in the present transfer than in the practice condition [142 versus 205 ms; $F(1,15)=32.3$, $p<.001$]. This slowing was particularly strong for the earlier keys [Fig. 4; $F(4,60)=7.7$, $p<.001$]. Foreperiod and consistency had no effect on execution rate [$F(1,15)=0.9$; $F(1,15)=1.5$, resp., $p>.20$].
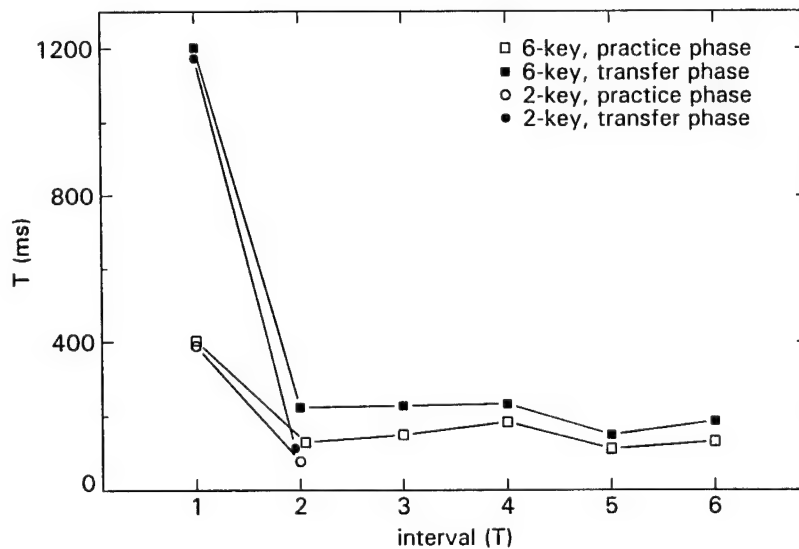

Fig. 4 Reaction time (T_1) and interkey intervals (T_2-T_6) in the last three sessions of the practice phase (no presequence and key specific cues) and transfer phase 2 (presequence, no key specific cues).

A Foreperiod (2) × Session (3) × Sequence (3) × Key (2) ANOVA on the arcsine transformed error proportions in the three 2-key sequences of transfer phase 2 showed that errors reduced with session [6.4%, 5.2%, 3.0%; $F(2,32)=4.7$, $p<.05$], that the 2-key varied mapping sequence had more errors than the 2-key consistent mapping sequences [7.0% versus 3.2% and 4.6%; $F(2,32)=4.8$, $p<.05$], and that more errors were made with the first key than with the second key [3.6% versus 1.3%; $F(1,16)=14.0$, $p<.01$].

A similar ANOVA on the two 6-key sequences showed that error rate reduced with session [average per key 3.6%, 3.0%, 1.8%; $F(2,32)=6.4$, $p<.01$], error rates differed for the various keys [$F(5,80)=2.5$, $p<.05$], and that the error distributions across keys were different for the consistent mapping and the varied mapping sequences [$F(5,80)=7.5$, $p<.001$]. The latter interaction indicated that the consistent mapping sequence had most errors at key positions 3 and 4 (4.5% and 4.6%, others below 3.2%) whereas the varied mapping sequence had most errors at the first key (6.3%, others below 2.6%).

A Practice versus Transfer (2) × Session (3) × Sequence (5) ANOVA on arcsine transformed errors at the first key of the 6-key sequences was carried out on practice Sessions 13-15 and transfer phase 2. This analysis showed that error rates were higher in transfer phase 2 than in the practice phase [3.5% versus 2.1%; $F(1,15)=24.3$, $p<.01$]. Planned comparisons showed that the increase was mainly due to varied mapping sequences: Error rate at the first key of consistent mapping sequences increased by 0.3% whereas error rate of varied mapping sequences increased by 3% [see Table II, $F(1,15)=14.8$, $p<.001$].

Table II Error percentages on first key of the sequences in the practice phase (Sessions 13−15) and transfer phase 2.

length	mapping	practice phase	transfer 2 phase
2	consistent	2.2%	1.9%
6	consistent	1.2%	1.3%
2	varied	3.3%	5.1%
6	varied	1.3%	5.6%
2	consistent	2.6%	3.5%

Comparison with a Foreperiod (2) × Practice versus Transfer (2) × Session (3) × Sequence (3) × Key (2) ANOVA of arcsine transformed errors in the 2-key sequences in transfer phase 2 and in Sessions 13-15 of the practice phase did not show that more errors were made in transfer phase 2 [$F(1,15)=0.9$, $p>.20$]. As regards 6-key sequences, a similar ANOVA showed that error rate even decreased in transfer phase 2 (practice: 4.4%, transfer: 2.3%; $F(1,15)=19.5$, $p<.001$].

4.3 Discussion

This phase examined whether, after practice with varied stimulus-to-sequence mappings, efficient response selection requires advance loading of translation rules into short term memory, whereas consistent mapping yields associative connections which do not require advance loading. This hypothesis was confirmed by the results. The difference between reaction times of sequences with consistent and varied stimulus-to-sequence mappings was much greater in this transfer phase than in the last three sessions of the practice phase. At the same time, error rate at the first key of each sequence, a major part of which can probably be attributed to selection errors, clearly increased in this transfer phase for varied mappings and not for consistent mapping. It appears that reduced preparation had a smaller effect on the selection of consistent mapping sequences than on the selection of varied mapping sequences.

A convincing indication that motor chunks had indeed developed in the practice phase, irrespective of mapping consistency, is that sequence execution was hardly affected by the absence of key specific cues. The entire sequences could be reproduced solely on basis of the imperative stimuli. Further support for the notion that motor chunks had developed comes from the finding that there were not more execution errors in the present transfer phase than in the practice phase. This is certainly expected if participants had been relying on key specific cues in the final practice sessions.

Notice that the fact that mapping consistency had an effect on initiation but not on execution is further evidence for the notion that independent processing stages are involved in selecting and executing motor chunks.

Apart from the relatively large consistency effect in this transfer phase there was a substantial increase of all sequence initiation intervals. Furthermore, sequence execution rate reduced somewhat, especially at the earlier keys. The fact that the presequence was introduced while, at the same time, key specific cues were removed, makes it unclear what exactly caused both effects. Yet, several studies have demonstrated the importance of general preparation mechanisms for the production of movement sequences (e.g., Rosenbaum, Inhoff & Gordon, 1984; Ziessler, Hänel & Sachse, 1990). It seems that even without detailed knowledge of the type of sequence to be produced, preparations can be made. It is feasible that the slight reduction in execution speed, especially in earlier sequence elements, can be attributed to insufficient general preparation due to time stress. This explanation is in line with the observation that the complexity effect recurred in the first session of the present transfer phase: The availability of motor chunks suffered from the lack of general preparation and sequences were programmed by loading again individual elements into the motor buffer (at the response selection level sequence information was apparently still available as was suggested earlier by the data in transfer phase 1). The observation that earlier key presses in the 6-key sequences were slowed more than later ones might suggest that executing earlier elements activates later elements via interelement associations (MacKay, 1987, 1990).

5   TRANSFER PHASE 3: REVERSAL PHASE

The distinction between practice effects at the response selection and at the sequence construction level is warranted only when it can be shown that these effects are independent. The practice phase provides evidence for independent stages in that, without foreperiod, sequence length and mapping consistency had additive effects and while responses could be selected prior to a go-signal, sequence construction was carried out not until immediately before sequence initiation. Serial responding in transfer phase 1 showed virtually no benefits of prior practice with movement sequences thereby suggesting that different representations are involved in the production of fixed movement sequences and in serial responding. Adding a presequence and removing key specific cues in transfer phase 2 confirmed that motor chunks had developed in the practice phase in that sequence production did not suffer much from reduced advance preparation and leaving out key specific cues whereas sequence initiation of consistent mapping sequences slowed less than of varied mapping sequences. Now, transfer phase 3 seeks to provide further evidence for separable effects of practice on response selection and sequence construction by reversing the stimulus-to-sequence mapping of consistently practiced sequences.

Several other studies that utilized *single* response movements demonstrated that RT increases dramatically if stimulus-to-response mapping is extensively and consistently practiced and then reversed (Kramer, Strayer & Buckley, 1990; Pashler & Baylis, 1991; Shiffrin & Dumais, 1981). This is generally attributed to the development of associations at the response selection level. These associations seem to form a passive mechanism that is under limited control of the participant and may be related to Kornblum *et al.*'s (1990) notion of automatic response activation when stimulus and response sets share properties (also see, e.g., Eimer, Hommel & Prinz, 1995). The notion that practice has independent effects at response selection and sequence construction predicts that reversal of consistently practiced mappings yields greater T_1s due to slower response selection without affecting the size of the complexity effect (which was practically absent after the practice phase anyway). Furthermore, sequence execution rate should not be affected because execution of the sequence, once constructed, and selection are carried out by different processes too.

An important matter concerns the effect of stimulus-to-sequence mapping reversal on T_1s of the remaining sequences. Reversal of stimulus-to-sequence mappings that once relied on associations will probably have the effect that ad hoc mapping rules are loaded into short-term memory (cf. Kornblum, Hasbroucq & Osman, 1990). This additional load on short term memory should not affect the third consistent mapping sequence because this sequence is still triggered through a passive association (cf. Logan, 1988). However, if indeed selection of varied mapping sequences depends on stimulus-to-sequence translation rules that are kept in short-term memory, T_1s of varied mapping sequences should suffer from mapping reversal. Hence, reversing the mapping of two consistently mapped sequences should increase T_1s of varied but not of the remaining consistently mapped sequence. Notice that according to the notion of independent processing stages, the (absence of the) complexity effect and sequence execution rate should not be affected by the reversal manipulation as these would originate at the sequence construction and execution stages, respectively.

5.1 Method

The procedure was the same as in transfer phase 2 except that the mappings of a consistently mapped 2-key and a consistently mapped 6-key sequence were reversed. Alternation of the mappings of stimuli on sequences of the two varied mapping sequences continued in the normal way. The stimulus-to-sequence mapping of the second consistently mapped 2-key sequence was not reversed.

This phase involved a single, two-block session which was carried out at as third session on Day 4 of the experiment immediately following the third transfer phase 2 session. The reversal effect was evaluated by comparing these two sessions.

5.2 Results

Fig. 5 shows the T_1 effect of reversing the mapping of two consistently mapped sequences in the reversal session as compared to the immediately preceding "normal" session. An ANOVA confirmed that the T_1 effect of reversal [$F(1,16)=55.9$, $p<.001$] differed for the five sequences [$F(4,64)=18.8$, $p<.001$]. Planned comparisons showed that reversal had a large and significant effect on the two reversed consistently mapped sequences [$F(1,16)=72$, $p<.001$] while it did not have an effect on the unaltered consistently mapping sequence [$F(1,16)=2.8$, $p>.10$]. The T_1 increase did not differ for the two reversed consistently mapping sequences [$F(1,16)=0.9$, $p>.20$]. T_1 to the two varied mapping sequences increased too [$F(1,16)=24.4$, $p<.001$]. The T_1 increase was greater for the two reversed consistent mapping sequences than for the varied mapping sequences [$F(1,16)=21.8$, $p<.001$]. Still, T_1s to consistent mapping sequences remained shorter than for varied mapping sequences [1295 ms versus 1370 ms; $F(1,16)=4.3$, $p=.05$].
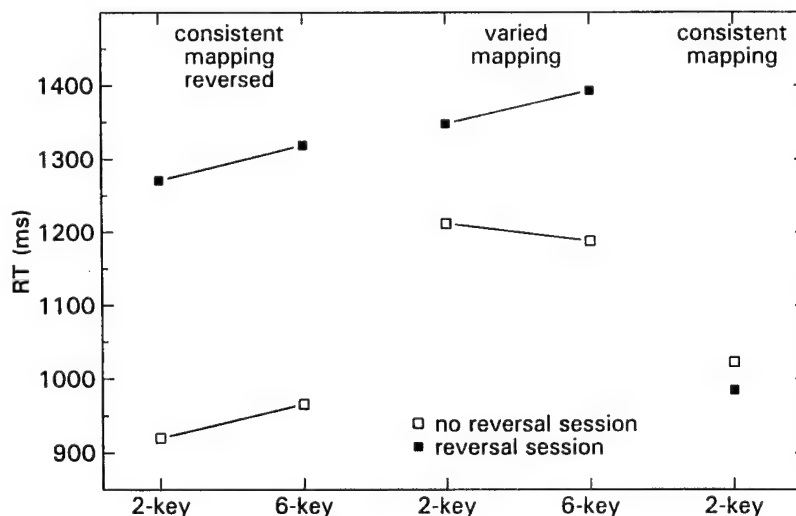

Fig. 5 T_1 to the five familiar sequences as a function of mapping reversal of two consistent mapping sequences.

Planned comparisons showed that the complexity effect did not reach significance before and after reversal [normal mapping session: consistent mapping sequence $F(1,16)=0.9$; varied mapping sequence $F(1,16)=0.3$; reversal mapping session: consistent mapping sequence $F(1,16)=1.5$; varied mapping sequence $F(1,16)=1.5$, all $ps > .20$]. Average interkey intervals in the 2-key and 6-key sequences were not affected by reversal either [$F(1,16)=0.6$; $F(1,16)=0.4$, resp., $ps > .20$].

Reversal did not have a main effect on error rate [2-key: 3.0% versus 2.5%; $F(1,16)=0.4$; 6-key: 9.4% versus 9.6%, $F(1,16)=0.2$, $ps > .20$]. In the normal mapping session, more errors were made in the varied mapping sequence than in the consistent mapping sequence (consistent mapping: 8.3%; varied mapping: 10.4%). After reversal this was the other way around [12.8% versus 6.5%; $F(1,16)=10.3$, $p<.01$]. To check whether execution was affected by reversal an error analysis was carried out while excluding errors on the first response which might be selection errors. This made the difference between consistent mapping and varied mapping disappear in the 2-key sequences [$F(1,16)=0.6$, $p>.20$] but in the 6-key sequences an interaction showed that while there was no consistency effect before reversal (6.6% versus 6.1%) more execution errors were made in the consistent mapping sequence than in the varied mapping sequence after reversal [9.3% versus 4.1%; $F(1,16)=5.2$, $p<.05$].

5.3   Discussion

Reversal of consistently practiced stimulus-to-sequence mappings slowed initiation of these sequences substantially. This corresponds with earlier reported descriptions of the reversal effect on RT for single responses but the present data are new in that they demonstrate that the reversal effect may hold for sequences of movements too. This finding casts some light on the nature of motor chunks too. Verwey (1994a) suggested that practice yields the possibility to select and program individual sequence elements during execution of their predecessor rather than that integrated representations (chunks) had developed. The present results reject this possibility. Selecting each individual element would most probably have relied upon short term memory. Then, mapping reversal should have slowed sequence execution rate too. This was not observed. Obviously, this does not mean that such a mechanism might not play a role in other situations (e.g., Verwey, 1996; Verwey & Dronkert, 1996).

Another important result is that the reversal instruction also increased T_1s of sequences with varied mappings, that is, mappings that had been alternated in the practice phase. In contrast, the reversal requirement did not affect T_1 of the sequence with the consistent mapping that was not changed. These are particularly interesting results in the light of the finding in the practice phase that the consistency effect did not increase much in the course of practice. There, this was attributed to the possibility to load stimulus-to-sequence translation rules in advance of each block of trials. In accordance with this post-hoc explanation, transfer phase 2 showed a much larger consistency effect when advance preparation was prevented by a presequence. Now, transfer phase 3 provides further evidence for the notion of advance loading of mapping rules in case of varied mappings by

showing that varied mapping sequences also suffer from reversing the mapping of consistently mapped sequences. The fact that the single, remaining consistent mapping sequence did not suffer is strong evidence for the notion that consistent mapping does not require advance loading of a stimulus-to-sequence mapping rule into short term memory.

Sequence execution rate and (absence of) the complexity effect were not affected by reversal. This is yet another indication for independence of response selection and sequence execution and of response selection and sequence construction.

Finally, on the assumption that the motor buffer is used for loading entire motor chunks and retrieving individual elements one by one (Verwey, 1994b), the absence of a sequence production rate effect suggest that short term memory and the motor buffer are independent buffers. This corroborates earlier indications for independent buffers (e.g., Fitzgerald, Tattersall & Broadbent, 1988; Logan, 1982; Schneider & Detweiler, 1988; Tattersall & Broadbent, 1991).

6   TRANSFER PHASE 4: DUAL SEQUENCE PRODUCTION

The notion that motor chunks lay the foundation for the proficient production of complex movement patterns suggests that motor chunks are robust units that are used in various different situations. A first aim of this final phase is to examine this claim by testing whether when two short, familiar sequences are performed in rapid succession, they are still carried out as separate parts. For relatively new movement sequences, the capacity of the motor buffer is limited to about four to six individual movements (Verwey, 1994b). With relatively long sequences one might still argue that they are executed separately because they do not fit the motor buffer together. However, if two familiar 2-key sequences are carried out in rapid succession the capacity of the motor buffer is sufficient to hold all four elements at the same time. If motor chunks are not robust, for example because they are highly context dependent, the two familiar sequences may just as easily be executed as a single sequence of four elements. In that case, all interkey intervals have a similar duration. However, when motor chunks are indeed robust, the second of the two familiar sequences will be preceded by a relatively long interkey interval.

A second issue concerns whether the second of two familiar sequences is prepared during execution of the first one, or whether preparation is distributed across a longer RT and a longer first key press of the second sequence. This can be investigated by correcting the initiation interval of the second sequence with the additional time taken to initiate the first sequence. If this corrected time is still smaller than initiation time of the second sequence when produced alone, one may conclude that preparation for the second of two sequences overlaps with execution of the first one.

Thirdly, there are various indications that concurrent preparation interferes with execution of the earlier parts of the sequence (Sternberg *et al.*, 1988; Van Galen, 1991; Verwey, 1996; Verwey & Dronkert, 1996). This suggests that sequence construction and sequence execu-

tion tap the same limited processing capacity or resource (Verwey, 1996). However, specific tests of the resource hypothesis argue against a resource explanation (McCann & Johnston, 1992; Pashler 1994). For one thing, resource theories do not specify a learning mechanism (Logan & Klapp, 1991). A better explanation seems to be that preparation and execution use the same short term memory. This reduces processing rate and, hence, sequence execution rate. Basically, it is difficult to distinguish explanations in terms of limited processing capacity and limited short term memory capacity. However, some studies suggest that the information required for producing a sequence need not immediately be removed from short term memory if the sequence is directly followed by another one. Evidence for this assumption has been reported by Sternberg *et al.* (1978, 1988) who found a sequence length effect on each of the elements of a movement sequence and argued that information for each individual sequence element is kept in a short term memory until sequence completion, even though the element has already been carried out. Furthermore, Rosenbaum *et al.* (1984) showed that mirror images of movement sequences with a certain spatial configuration are initiated faster than entirely different sequences and argued that when information has been retrieved from short term memory, the information is not immediately erased (Rosenbaum, 1991; also see e.g., Hommel, 1994; McLean & Shulman, 1978). If, indeed, information decays with a limited speed in short term memory after production of the first of two sequences, the second sequence might be executed more slowly than when it is executed alone because short term is still loaded by information from the earlier sequence. This contrasts with the prediction of a limited processing capacity model that says that processing capacity is unaffected by whether or not a sequence happened to be executed before or not, and, hence, that a sequence will be executed at the same rate irrespective of whether or not an earlier sequence has just been produced.

Finally, in line with the notion that the time required for producing elements of the same motor chunk should be more equal than for elements of different motor chunks (e.g., Sternberg, Knoll & Turock, 1990), Young and Schmidt (1990) argued that correlations reflect whether movement parts belong to the same integrated unit. This notion was supported in that correlations between the times of certain parts of a coincident-timing task were higher than between some other parts. Later studies confirmed this notion (Schneider & Schmidt, 1995; Young & Schmidt, 1990). However, Gentner (1987, p.274) argued that, "… when the details of timing are not an explicit part of the task, they will be determined by other considerations, such as minimizing energy consumption …". For instance, the timing of actual movements may be affected by delays between central commands and resulting movements (e.g., Heuer, 1988). So, the usefulness of correlations as criterion for the use of motor chunks may depend on the timing requirements of the task. Because timing was essential in Young and Schmidt's (1990) task and not in the present task, it remains to be seen whether correlations also indicate in the present task that different motor chunks are being used.

In short, this final transfer phase tested four hypotheses: (a) motor chunks are robust units which are still used when the elements of two sequences together fit the motor buffer. (b) Movement sequences are performed more slowly when they follow another sequence because information for the first sequence remains in short term memory after its execution has finished. (c) Preparation for the second of two movement sequences overlaps with

execution of the first sequence. (d) Correlations between intervals within a familiar sequence are higher than those between intervals of successive familiar sequences. These hypotheses were tested by having the practiced participants from the earlier phases, produce either one or two familiar sequences in rapid succession. To reduce effects of advance preparation, the imperative stimuli were again preceded by a short series of random key presses.

6.1 Method

Participants had their fingers on the same keys as before and the same set of nine squares was displayed at the screen. As in transfer phase 2 and 3, each trial started with eight to twelve random keys but this was now followed by presentation of one or two imperative stimuli. It was the participant's task to produce the one or two associated sequences in rapid succession.

In order to limit the number of possible sequence combinations and to reduce possible response selection effects, only consistent mapping sequences were involved in this phase. Hence, this phase involved the following combinations: 2/0 (first sequence length 2, second length 0; i.e. single sequence), 2/2 (two 2-key sequences), 2/6, 6/0, and 6/2. A sequence was never repeated in a single trial. As two 2-key consistent mapping sequences had been practiced there were two alternatives for the 2-key sequences. This allowed two versions of the 2/2 combination.

This transfer phase included two 54 trial sessions which were performed at Day 4 following the transfer phase 3 reversal session.

6.2 Results

Fig. 6 shows T_1s and interkey intervals for all single sequences and combinations of sequences as a function of their length and context. The figure clearly shows that when the 2-key sequences followed another sequence [i.e., (2)2 and (6)2], their first key press was slower than the remaining ("real") interkey intervals. Planned comparisons confirmed this: the first key of the 2-key sequence (T_1) was slower in (2)2 than the remaining interkey intervals [i.e., T_2 of 2(2) and (2)2; $F(1,16)=80.5$, $p<.001$]. This was also found when the 2-key sequence followed a 6-key sequence [i.e., in (6)2, $F(1,16)=56.8$, $p<.001$] and when the 6-key sequence followed a 2-key sequence [$F(1,16)=92.9$, $p<.001$]. So, the 2-key sequences remained to be executed as robust units.

Execution rate of 2-key sequences was slower when they were preceded or followed by another sequence than when produced alone [113 ms versus 144 ms; $F(1,16)=25.0$, $p<.001$]. The 2-key sequences were executed slightly slower in combination with a 6-key sequence than in combination with the other 2-key sequence [147 ms versus 139 ms; $F(1,16)=5.0$, $p<.05$] but whether the 2-key sequence was first or second did not affect execution rate [$F(1,16)=0.8$, $p>.20$]. Average production rate of the 6-key sequences was also higher when executed alone than together with another (2-key) sequence [117 ms versus

186 ms, $F(1,16)=7.6$, $p<.05$]. Whether the 6-key sequence was first or second when combined with a 2-key sequence did not affect execution rate [183 versus 190 ms, $F(1,16)=1.9$, $p>.20$]. Apparently, slowing resulted from short-term memory load.
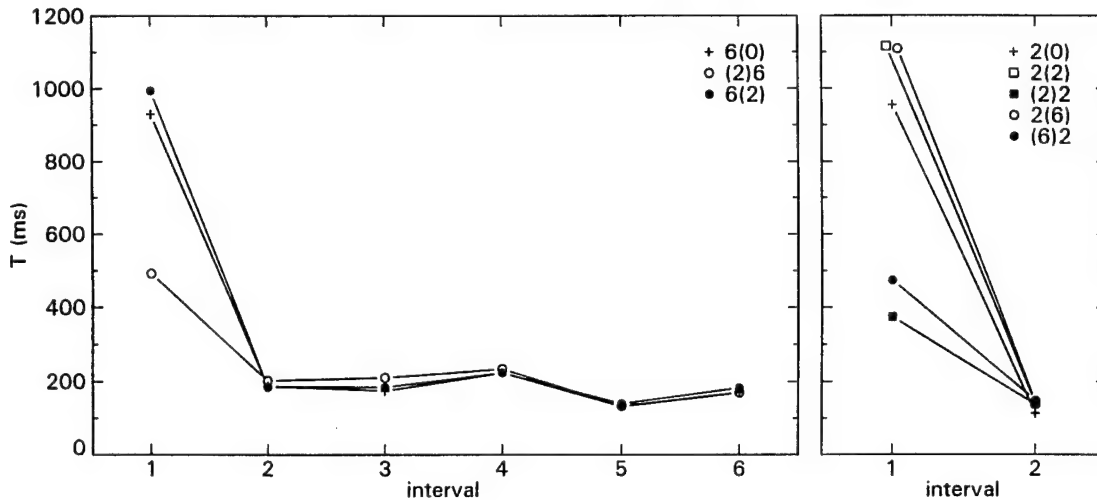

Fig. 6   Response times of 6- and 2- key sequences as a function of their context: alone [2(0) and 6(0)], prior to another 2-key [2(2) and 6(2)] or 6-key sequence [2(6)], and following another 2-key [(2)2 and (2)6] or 6-key sequence [(6)2].

To determine whether preparation of the second sequence overlapped with execution of the first, the longer time taken to initiate (2)2, as compared to 2(0), was added to the interval preceding the first key of (2)2. The resulting interkey interval was named $(2)2_{cor}$. $(2)6_{cor}$ was computed in a similar way. Comparison of 2(0), $(2)2_{cor}$, and $(6)2_{cor}$ showed that T_1 of 2(0) was clearly longer than the initiation intervals of $(2)2_{cor}$ and $(6)2_{cor}$ [955 ms, 539 ms, 535 ms, resp.; $F(2,32)=124.$, $p<.001$]. Over 400 ms was gained in initiating familiar 2-key sequences when these followed another familiar sequence. Planned comparison confirmed that the statistically significant effect was due to the difference between 2(0) versus $(2)2_{cor}$ and $(6)2_{cor}$ [$F(1,16)=404.0$, $p<.001$]. In a similar way, 6(0) was compared to $(2)6_{cor}$. This showed that T_1 in 6(0) was 284 ms longer than in $(2)6_{cor}$ [929 versus 645 ms; $F(1,16)=90.9$, $p<.001$]. Planned comparison showed that the 418 ms gain of (2)2 was significantly greater than the 284 ms gain for (2)6 [$F(1,16)=12.2$, $p<.01$].

Fig. 6 also shows that RT (i.e. T_1 of the first sequence) was longer with two than with one sequence [see Fig. 6; planned comparison of 2(0) versus 2(2) and 2(6): $F(1,16)=65.4$, $p<.001$; 6(0) versus 6(2): $F(1,16)=16.1$, $p<.001$]. Planned comparisons further showed that in the 2-key sequences, RT was not affected by the size of the second sequence but only by its presence: RT in 2(0) differed from RT in 2(2) [$F(1,16)=70.3$, $p<.001$] and RT in 2(6) [$F(1,16)=47.5$, $p<.001$] whereas RT did not differ for 2(2) and 2(6) [$F(1,16)=0.2$, $p>.20$].

Next, RT of all pairs of sequences were compared, that is 2(2), 2(6) and 6(2). This showed a difference between these RTs [$F(2,32)=7.7$, $p<.001$] suggesting that RT increased more when a 2-key sequence was followed by a second sequence than when a 6-key sequence was followed by another sequence. Planned comparisons confirmed this and also showed that the length of the second sequence did not affect RT [2(2) versus 2(6) $F(1,16)=0.2$, $p>.20$; 2(2) versus 6(2) $F(1,16)=7.5$, $p<.05$; 2(6) versus 6(2) $F(1,16)=9.1$, $p<.01$].

Finally for each participant, correlations between pairs of responses in combinations of sequences were computed per session. This analysis did not show that correlations were higher between interkey intervals of responses belonging to a familiar sequence than between responses of different familiar sequences: in combinations of 2- and 6-key sequences the average correlation between interkey intervals preceding keys of the same sequence amounted to .14, whereas the correlation between interkey intervals of successive sequences was .14 too. For combinations of two 2-key sequences these correlations were .08 for within-sequence intervals and .18 for between-sequence intervals. Exclusion of the first interval of each sequence, which might be affected by initiation processes, yielded comparable results.

T_1 and interkey analyses involved only sequences without errors. ANOVAs on arcsine transformed error rates showed few systematic effects. For combinations of 2-key sequences followed by 6-key sequences, error rate per individual key ranged between 0.6% and 4.4%. When 6-key sequences were ensued by 2-key sequences, error percentages ranged from 1.2 to 2.4 but the first key of the 2-key sequence had an error rate of 5.5% [$F(7,112)=6.3$, $p<.001$]. Analysis of error rates of the combination of two 2-key sequences showed error percentages per key between 1.5% and 2.6%. Finally, average error rates of individual keys of sequences executed in isolation were 1.9% for 2-key sequences and 2.1% for 6-key sequences.

To recapitulate, when a familiar sequence followed another familiar sequence, the interkey interval preceding the second sequence was always longer than the other within-sequence intervals. Yet, initiating a familiar sequence was faster when that sequence followed another sequence than when it was the first one in a series of two or when it was produced alone. This rapid initiation of second sequences was greater when a 2-key sequence followed another 2-key sequence than when a 6-key sequence followed a 2-key sequence. RT of a series of two sequences was greater than RT of a single sequence which effect was stronger if the first sequence was a 2-key sequence. Sequences were executed more slowly when they were combined with another sequence, irrespective of whether they were first or second. Finally, correlations between interkey intervals of two successive sequences showed no effect of whether the two keypresses belonged to the same or to separate sequences.

6.3   Discussion

The results are entirely in line with the notions that (a) motor chunks are so robust that they remain to be used even when the combination of the sequences could have been produced as a single sequence, (b) interference between simultaneous preparation and execution of

movement sequences is caused by short term memory load rather than by a limited processing capacity, (c) preparation for the second of two movement sequences overlaps with execution of the first sequence, (d) correlations can not always be used as an indicator for the use of motor chunks.

Evidence for the robustness of motor chunks is that a relatively long interval preceded the start of each second, familiar sequence even when two 2-key sequences followed each other so that the total number of keys together would have fitted the motor buffer. Besides, the present results showed no indications for a complexity effect in terms of the total number of keypresses, which would be expected if a new four-element sequence was produced rather than two familiar 2-key sequences. The relatively long inter-chunk interval is in line with the idea that loading the motor buffer can not start before the earlier sequence has been finished (i.e., the buffer is ready for reloading).

Even though the familiar sequences appear to be carried out as separate units, initiating the second of two successive sequences took less time than when it was carried out in isolation (i.e., without another one). Even when the longer time to initiate the first sequence was taken into account, a considerable gain was observed relative to the RT following the serial response task. This is an indication for concurrent preparation of the second sequence during execution of the first. Interestingly, the gain in initiating the second familiar sequence was higher with two 2-key sequences than with a 2-key sequence followed by a 6-key sequence. This suggests that when sequences of different lengths are carried out in succession, a general reorganization is required. It corresponds to earlier findings for a general preparatory process which occurs once the length of the sequence is known (Ziessler *et al.*, 1990).

Further evidence for concurrent preparation of the second sequence is that RT increased more when a 2-key sequence was followed by a second (2- or 6-key) sequence than when a 6-key sequence was followed by a second sequence. This difference can not be explained by a longer time taken for identifying two stimuli but it is in line with a higher degree of concurrent preparation when the 6-key sequence is first. Probably, the 6-key sequence gives more time for concurrent preparation.

As observed in earlier studies, production rate of one sequence decreased when another sequence had to be produced too (Verwey, 1996; Verwey & Dronkert, 1996). The present data show that this slowing occurs irrespective of whether a sequence is first or second (and last). This is a theoretically important result as it rejects the notion advanced before (Verwey, 1996), that slowing would be due to a limited processing capacity. Instead, on the assumption that information for a sequence is not erased from short term memory after that sequence has been produced, this finding is more in line with an increased short term memory load. Additional evidence for this conjecture is that the 2-key sequences were slowed more when preceded by a 6-key sequence than by a 2-key sequence: 6-key sequences are likely to load short term memory more than 2-key sequences.

In contrast to results obtained with a coincident timing task, correlations between interkey intervals of two successive sequences showed no effect of whether the two keypresses belonged to the same or to separate familiar sequences. In fact, this confirms research which

could not show invariant timing in skilled motor behavior either (Burgess-Limerick, Neal & Abernethy, 1992; Wann & Nimmo-Smith, 1990). The correlations found in the coincident-timing task reported by Schmidt and colleagues (Schneider & Schmidt, 1995; Young & Schmidt, 1990) were probably so high because timing was an explicit requirement for performing the task well. Given the present evidence that motor chunks had indeed developed whereas invariant timing did not occur, correlations between distinguishable elements in a sequential movement task appear simply unsuited for indicating units of action—unless timing is a crucial aspect of the task. Yet, one might wonder whether the correlations are not merely an indication that timing is essential rather than that motor units have developed.

In summary, transfer phase 4 provides evidence for the notion that motor chunks are also used in contexts different from how they were practiced, even when two successive 2-key sequences are carried out in rapid succession. Evidence for preparation of the second sequence during execution of the first sequence was provided by a relatively fast initiation of the second sequence and the finding that RT increased more when a 2-key sequence was followed by another sequence than when a 6-key sequence was followed by another sequence. The observation that sequences were also carried out more slowly when they followed another sequence and that this effect was stronger when the other sequence was longer, suggests a short term memory load explanation for the interference observed when two sequences are carried out in succession. Finally, in the present sequence production task with no emphasis on timing, the existence of motor chunks could not be proven with correlations. It is entirely possible that this criterion is useful only for showing that timing is consistent rather than that fixed units in terms of motor chunks are being used.

7   GENERAL DISCUSSION

The objective of this study was to obtain evidence for a model of skilled production of movement patterns in which independent processing stages are responsible for (a) selecting representations of integrated movement sequences, (b) constructing sequences from these representations by loading information into a short term motor buffer, and (c) executing each individual sequence element in the motor buffer. The present results support such a model.

Motor chunk development

The present data provide ample evidence that motor chunks developed with practice. It is now clear that this happens not only in the cycling keypressing task that was used before (Verwey, 1996; Verwey & Dronkert, 1996) but also in a choice reaction time context. Chunk development was evidenced by (a) a reduction of the complexity effect with practice, (b) the development of a fixed error pattern across the sequence, (c) the possibility to reproduce the entire sequence without key specific cues, and (d) the relatively long interkey intervals preceding each second familiar sequence when two sequences were produced in rapid succession. Further evidence came from the finding that the complexity effect did not return after reversal of the two consistent stimulus-to-response mappings. Only when a pre-sequence was introduced and key specific cues were removed did the complexity temporarily

return. It is possible that the availability of motor chunks depends on setting the appropriate processing stages in advance.

Despite this strong evidence that motor chunks had developed, correlations between interkey intervals were not higher within than between two familiar sequences. The last transfer phase suggests that familiar sequences can be regarded as if they are simple responses in that indications were obtained for a complexity effect at the sequence level. That is, it takes more time to initiate two than one sequence. This is entirely in line with findings that sequences of written letters, which themselves are movement sequences as well, behave as sequences of single integrated elements (e.g., Van Galen, 1991). The complexity effect observed with sequences of relatively long lasting elements will probably level off quickly because, once the performer has motor chunks for the individual elements, he or she can start preparing each individual element during the relatively long time it takes to execute the preceding element. Evidence for this conjecture can also be found in the rapid levelling off found with sequences of aiming movements (e.g., Christina *et al.*, 1985; Christina & Rose, 1985; Fischman, 1984; Klapp *et al.*, 1979; see Verwey, 1994b for an overview). In brief, the fact that leveling off of the complexity effect is so different for sequences of different movement elements can be explained so nicely in terms of concurrent processing, shows that the notion of additive processing stages should be extended for more complex tasks, rather than forgotten.

Practice effects at the response selection stage

In line with the notion that familiar sequences are controlled by motor chunks, there is clear evidence that the selection of entire movement sequences is easy after practice in consistent mapping conditions. This is attributed to the development of stimulus-to-motor chunk associations just as with stimulus-to-response associations when relatively simple responses are selected. The development of such associations is indicated by findings that (a) varied mappings yielded longer RTs than consistent mappings, (b) this difference increased considerably when a presequence was introduced in the second transfer phase, and (c) reversal of the consistent stimulus-to-response mappings led to a dramatic T_1 increase of the sequences with the reversed mappings and of the sequences with the varied mappings while this was not the case with an unaltered consistent mapping.

The fact that initiation time of varied mapping sequences was more vulnerable to pre-sequences and mapping reversal than consistent mapping sequences suggests that stimulus-to-motor chunk selection rules had developed which were loaded into short term memory before selection could take place whereas consistent mapping yielded associations which do not require advance loading and automatically trigger the corresponding response or motor chunk.

Independence of response selection, sequence construction and sequence execution

Motor chunk development and stimulus-to-response associations appear independent effects of practice because the complexity effect, resulting from the sequence construction stage, was additive to the effect of mapping consistency which is a response selection variable.

Also, the existence of motor chunks did not improve performance in the serial response task, which is assumed to rely on response priming at the response selection stage. The data corroborate Verwey's (1994b) suggestion that response selection precedes sequence construction by the finding in the practice phase that the response selection variable mapping consistency did not have an effect on initiation time in the presence of a foreperiod while the complexity effect was not affected by foreperiod. This does not only support the notion that response selection precedes sequence construction, it is also in line with the notion that the result of response selection, which is probably some abstract memory representation, can be kept in a short term buffer for some time whereas this is not the case with the sequence representation in the motor buffer as built during sequence construction (Canic & Franks, 1989; Sternberg *et al.*, 1978). Notice that the present data show that a foreperiod may obscure response selection effects (cf. Simon & Craft, 1989). Future studies on response selection variables should take this into account.

Sequence execution also appeared independent of response selection. Mapping reversal, which is assumed to increase short term memory load because an association is replaced by an additional stimulus-to-response selection rule, did not affect sequence execution rate nor did mapping consistency in the practice and in later phases. However, the requirement to execute two sequences did reduce execution rate of both sequences. Given that this slowing was found with the second sequence too suggests that slowing was not caused by a limited processing capacity or resource but by the additional load on short term memory. It remains unclear why more complex response selection, assumed to cause greater short term memory load, did not affect sequence execution rate whereas the requirement to generate another sequence did reduce execution rate. Perhaps different short term buffers are involved, one for holding response selection rules and one for maintaining the second stimulus or already selected motor chunk. In contrast, one might consider that there is only one short term memory but that cross talk is higher with two sequences than with one sequence and more complex mapping rules (Hirst & Kalmer, 1987; Navon & Miller, 1987). The present study does not provide information on this issue.

Execution rate also reduced when a presequence was introduced and key specific cues were removed. Here, slowing was probably caused by reduced preparation. The sequence may have been produced on the basis of a representation at the response selection level. The possibility that removal of the key specific cues was responsible for slowing seems unlikely in that interkey intervals were too short to allow responses to these cues. Also, the explicit need to respond to key specific cues in serial responding did not gain from the occurrence of familiar sequences.

Applications

The present results are closely related to the concept of *mental workload* as used in human factors and ergonomics research. Whereas a commonly agreed definition of mental workload is lacking, researchers generally acknowledge that mental workload is closely connected to the attentional demands of task performance. Many studies have shown that mental workload reduces considerably with practice and that people are less loaded as they are more experienced with a task. For example, Verwey (in prep.) showed that inexperienced drivers are

loaded considerably more in complex driving situations than experienced drivers. The present results show at least part of the underlying mechanism: if people have a large repertoire of movement patterns and also know in which situations to "launch" these, attention is free for anticipating further actions. In effect, more time will be available to attend to other things and mental workload will be low.

Conclusions

While many models of practice describe effects of practice (e.g., Crossman, 1959; Logan, 1988; Newell & Rosenbloom, 1981) they are not able to predict in great detail the changes that occur in perceptual motor tasks with practice. For example, resource theories do not specify a learning mechanism and, hence, cannot make detailed predictions on effects of practice (Logan & Klapp, 1991). Still, there are many indications that performance gains from the presence of consistent task components even if the total task is not consistent (e.g., Fisk, Oransky & Skedsvoldy, 1988; Fisk & Schneider, 1984). The results of the present study demonstrate that the notion of independent, additive processing stages does a good job in describing the phenomena found with sequence production and the changes that occur with practice. That is, the present results are in line with a multi-stage model of practice. The present data emphasize the need to distinguish between response selection and sequence construction. The present study devoted less attention to the processing stages which are responsible for recognizing stimuli and for executing the content of the motor buffer. This should be the focus of future research. Other types of tasks will probably show that learning occurs at these stages too. So, one may have tasks in which perceptual learning and response selection are involved, such as in learning to read notes and playing a musical instrument, or tasks in which individual movement elements of a movement have to be practiced.

All in all, the present data demonstrate that advanced versions of traditional "box" thinking, including notions such as concurrent processing and chunk development, yield useful insights in the mechanisms underlying skilled sequence production. The indications for concurrent processing of different pieces of information at different stages, here and in earlier studies (Verwey, 1996; Verwey & Dronkert, 1996), are entirely in line with contemporary notions about independent processing stages that operate simultaneously on different features of a stimulus (e.g., Eimer *et al.*, 1995; Levy & Pashler 1995; Miller, 1982, 1988). Future research should find out more precisely when information is broken down into separable pieces that are processed independently. It is my belief that this will not undermine the assumption of serial discrete processing stages but, rather, reveal the elementary pieces of information that can be handled by the human information processing system.

REFERENCES

Burgess-Limerick, R., Neal, R.J. & Abernethy, B. (1992). Against relative timing invariance in movement kinematics. *Quarterly Journal of Experimental Psychology, 44A,* 705-722.

Canic, M.J. & Franks, I.M. (1989). Response preparation and latency in patterns of tapping movements. *Human Movement Science, 8,* 123-139.

Christina, R.W., Fischman, M.G., Lambert. A.L. & Moore, J.F. (1985). Simple reaction time as a function of response complexity. Christina *et al.* (1982) revised. *Research Quarterly for Exercise and Sport, 56,* 316-322.

Christina, R.W. & Rose, D.J. (1985). Premotor and motor reaction time as a function of response complexity. *Research Quarterly for Exercise and Sport, 56,* 306-315.

Cohen, A., Ivry, R.I. & Keele, S.W. (1990). Attention and structure in sequence learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 16,* 17-30.

Crossman, E.R.F.W. (1959). A theory of the acquisition of speed skill. *Ergonomics, 2,* 153-166.

Curran, T. & Keele, S.W. (1993). Attentional and nonattentional forms of sequence learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 19,* 189-202.

Duncan, J. (1978). Response selection in spatial choice reaction: Further evidence against associative models. *Quarterly Journal of Experimental Psychology, 30,* 429-440.

Eimer, M., Hommel, B. & Prinz, W. (1995). S-R compatibility and response selection. *Acta Psychologica, 90,* 301-313.

Fischman, M.G. (1984). Programming time as a function of number of movement parts and changes in movement direction. *Journal of Motor Behavior, 16,* 405-423.

Fisk, A.D. & Schneider, W. (1984). Consistent attending versus consistent responding in visual search: Task versus component consistency in automatic processing development. *Bulletin of the Psychonomic Society, 22,* 330-332.

Fisk, A.D., Oransky, N.A. & Skedsvoldy, P.R. (1988). Examination of the role of "Higher-order" consistency in skill development. *Human Factors, 30,* 567-581.

Fitzgerald, P., Tattersall, A.J. & Broadbent, D.E. (1988). Separating central mechanisms by POCs: Evidence for an input-output buffer. *Quarterly Journal of Experimental Psychology, 40A,* 109-134.

Gentner, D.R. (1987). Timing of skilled motor performance: Test of the proportional duration model. *Psychological Review, 94,* 255-276.

Gottsdanker, R. & Shragg, G.P. (1985). Verification of Donders' subtraction method. *Journal of Experimental Psychology: Human Perception and Performance, 11,* 765-776.

Grudin, J.T. (1983). Error patterns in novice and skilled transcription typing. In W.E. Cooper (Ed.), *Cognitive Aspects of Skilled Type-Writing* (pp. 121-145). New York: Springer Verlag.

Haggard, P. (1991). Task coordination in human prehension. *Journal of Motor Behavior, 23,* 25-37.

Hartman, M., Knopman, D.S. & Nissen, M.J. (1989). Implicit learning of new verbal associations. *Journal of Experimental Psychology: Learning, Memory & Cognition, 15,* 1070-1082.

Henry, F.M. (1980). Use of simple reaction time in motor programming studies: A reply to Klapp, Wyatt, and Lingo. *Journal of Motor Behavior, 12,* 163-168.

Henry, F.M. & Rogers, D.E. (1960). Increased response latency for complicated movements and a "memory drum" theory of neuromotor reaction. *Research Quarterly, 31,* 448-458.

Heuer, H. (1988). Testing the invariance of relative timing: Comments on Gentner. *Psychological Review, 95,* 552-557.

Hirst, W. & Kalmer, D. (1987). Characterizing attentional resources. *Journal of Experimental Psychology: General, 116,* 68-81.

Hommel, B. (1994). Spontaneous decay of response code activation. *Psychological Research, 56, 261-268.*

Hulstijn, W. & Van Galen, G.P. (1983). Programming in handwriting: Reaction time and movement time as a function of sequence length. *Acta Psychologica, 54,* 23-49.

Hulstijn, W. & Van Galen, G.P. (1988). Levels of motor programming in writing familiar and unfamiliar symbols. In A.M. Colley & J.R. Beech (Eds.), *Cognition and Action in Skilled Behaviour* (pp. 65-85). Amsterdam: North-Holland.

Inhoff, A.W., Rosenbaum, D.A., Gordon, A.M. & Campbell, J.A. (1984). Stimulus-response compatibility and motor programming of manual response sequences. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 724-733.

Klapp, S.T. (1977). Response programming, as assessed by reaction time, does not establish commands for particular muscles. *Journal of Motor Behavior, 9,* 301-312.

Klapp, S.T., Abbott, J., Coffman, K., Greim, D., Snider, R. & Young, F. (1979). Simple and choice reaction time methods in the study of motor programming. *Journal of Motor Behavior, 11,* 91-101.

Kornblum, S., Hasbroucq, T. & Osman, A. (1990). Dimensional overlap: Cognitive basis for stimulus-response compatibility - A model and a taxonomy. *Psychological Review, 97,* 253-270.

Kramer, A.F., Strayer, D.L. & Buckley, J. (1990). Development and transfer of automatic processing. *Journal of Experimental Psychology: Human Perception and Performance, 16,* 505-522.

Levy, J. & Pashler, H. (1995). Does perceptual analysis continue during selection and production of speeded response? *Acta Psychologica, 90,* 245-260.

Lewicki, P., Czyzewska, M. & Hoffman, H. (1987). Unconscious acquisition of complex procedural knowledge. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 13,* 523-530.

Lewicki, P., Hill, T. & Bizot, E. (1988). Acquisition of procedural knowledge about a rule of stimuli that cannot be articulated. *Cognitive Psychology, 20,* 24-37.

Logan, G.D. (1979). On the use of a concurrent memory load to measure attention and automaticity. *Journal of Experimental Psychology: Human Perception and Performance, 5,* 189-207.

Logan, G.D. (1980). Short-term memory demands of reaction-time tasks that differ in complexity. *Journal of Experimental Psychology: Human Perception and Performance, 6,* 375-389.

Logan, G.D. (1982). Time, information, and the various spans in typewriting. In W.E. Cooper (ed.), *Cognitive Aspects of Skilled Typewriting* (pp. 197-224). New York: Springer-Verlag.

Logan, G.D. (1988). Toward an instance theory of automatization. *Psychological Review, 95,* 492-527.

Logan, G.D. & Klapp, S.T. (1991). Automatizing alphabet arithmetic: I. Is extended practice necessary to produce automaticity? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 17,* 179-195.

Logan, G.D., Zbrodoff, N.J. & Fostey, A.R.W. (1983). Costs and benefits of strategy construction in a speeded discrimination task. *Memory & Cognition, 11,* 485-493.

MacKay, D.G. (1982). The problems of flexibility, fluency, and speed-accuracy trade-off in skilled behavior. *Psychological Review, 89,* 483-506.

MacKay, D.G. (1987). Asymmetries in the relationship between speech perception and production. In H. Heuer & A.F. Sanders (Eds.), *Perspectives on Perception and Action* (pp. 301-333). Hillsdale, NJ: Erlbaum.

MacKay, D.G. (1990). Aspects of the theory of action, attention, and awareness. In W. Prinz & O. Neumann (Eds.), *Relationships between Perception and Action: Current Approaches* (pp. 269-303). Berlin: Springer.

Marteniuk, R.G. & MacKenzie, C.L. (1980). Information processing in movement organization and execution. In R.S. Nickerson (Ed.), *Attention and Performance VIII* (pp. 29-57). Hillsdale, NJ: Erlbaum.

McCann, R.S. & Johnston, J.C. (1992). The locus of the single channel bottleneck in dual task interference. *Journal of Experimental Psychology: Human Perception & Performance, 18,* 471-484.

McLean, J.P. & Shulman, G.L. (1978). On the construction and maintenance of expectancies. *Quarterly Journal of Experimental Psychology, 30,* 441-454.

Miller, J. (1982). Discrete versus continuous stage models of human information processing: In search of partial output. *Journal of Experimental Psychology: Human Perception and Performance, 8,* 273-296.

Miller, J. (1988). Discrete and continuous models of human information processing: Theoretical distinctions and empirical results. *Acta Psychologica, 67,* 191-257.

Mowbray, G.H. & Rhoades, M.V. (1959). On the reduction of choice reaction times with practice. *Quarterly Journal of Experimental Psychology, 11,* 16-23.

Navon, D. & Miller, J. (1987). Role of outcome conflict in dual-task interference. *Journal of Experimental Psychology: Human Perception and Performance, 13,* 435-448.

Newell, A. & Rosenbloom, P. (1981). Mechanisms of skill acquisition and the law of practice. In J.R. Anderson (Ed.), *Cognitive Skills and their Acquisition* (pp. 1-55). Hillsdale, NJ: Erlbaum.

Nissen, M.J. & Bullemer, P. (1987). Attentional requirements of learning: Evidence from performance measures. *Cognitive Psychology, 19,* 1-32.

Pashler, H. (1989). Dissociations and dependencies between speed and accuracy: Evidence for a two-component theory of divided attention in simple tasks. *Cognitive Psychology, 21,* 469-514.

Pashler, H. (1994). Overlapping mental operations in serial performance with preview. *Quarterly Journal of Experimental Psychology, 47A,* 161-191.

Pashler, H. & Baylis, G. (1991). Procedural learning: 1. Locus of practice effects in speeded choice tasks. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 17,* 20-32.

Posner, M.I. & Snyder, C.R.R. (1975). Attention and cognitive control. In R.L. Solso (Ed.), *Information Processing and Cognition*. Hillsdale, NJ: Erlbaum.

Proctor, R.W. & Dutta, A. (1993). Do the same Stimulus-Response relations influence choice reactions initially and after practice? *Journal of Experimental Psychology: Learning, Memory & Cognition, 19,* 922-930.

Rosenbaum, D.A. (1991). *Human Motor Control.* San Diego, CA: Academic Press.

Rosenbaum, D.A., Inhoff, A.W. & Gordon, A.M. (1984). Choosing between movement sequences: A Hierarchical Editor Model. *Journal of Experimental Psychology: General, 113,* 372-393.

Sanders, A.F. (1990). Issues and trends in the debate on discrete vs. continuous processing of information. *Acta Psychologica, 74,* 1-45.

Schneider, D.M. & Schmidt, R.A. (1995). Units of action in motor control: Role of response complexity and target speed. *Human Performance, 8,* 27-49.

Schneider, W. (1985). Toward a model of attention and the development of automatic processing. In M.I. Posner & O.S.M. Marin (Eds.), *Attention and Performance XI* (pp. 475-492). Hillsdale, NJ: Erlbaum.

Schneider, W. (1988). Micro Experimental Laboratory: An integrated system for IBM-PC compatibles. *Behavior Research Methods, Instrumentation, and Computers, 20,* 206-217.

Schneider, W. & Detweiler, M. (1988). The role of practice in dual-task performance: Toward workload modeling in a connectionist/control architecture. *Human Factors, 30,* 539-566.

Segalowitz, S.J. & Graves, R.E. (1990). Suitability of the IBM XT, AT, and PS/2 keyboard, mouse, and game port as response devices in reaction time paradigms. *Behavior, Research Methods, Instruments & Computers, 22,* 283-289.

Shaffer, L.H. (1973). Latency mechanisms in transcription. In S. Kornblum (Ed.), *Attention and Performance IV* (pp. 435-446). New York: Academic Press.

Shiffrin, R.M. & Dumais, S.T. (1981). The development of automation. In J.R. Anderson (Ed.), *Cognitive Skills and their Acquisition* (pp. 111-140). Hillsdale, NJ: Erlbaum.

Simon, J.R. & Craft, J.L. (1989). The effect of prediction accuracy on choice reaction time. *Memory and Cognition, 17,* 503-508.

Stadler, M.A. (1992). Statistical structure and implicit learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18,* 318-327.

Sternberg, S. (1969). The discovery of processing stages: Extensions of Donders' method. *Acta Psychologica, 30,* 276-315.

Sternberg, S., Knoll, R.L., Monsell, S. & Wright, C.E. (1988). Motor programs and hierarchical organization in the control of rapid speech. *Phonetica, 45,* 175-197.

Sternberg, S., Knoll, R.L. & Turock, D.L. (1990). Hierarchical control in the execution of action sequences: Tests of two invariance properties. In M. Jeannerod (Ed.), *Attention and Performance XIII* (pp. 3-55). Hillsdale, NJ: Erlbaum.

Sternberg, S., Monsell, S., Knoll, R.L. & Wright, C.E. (1978). The latency and duration of rapid movement sequences: comparisons of speech and typewriting. In G.E. Stelmach (Ed.), *Information Processing in Motor Control and Learning* (pp. 117-152). New York: Academic Press.

Tattersall, A.J. & Broadbent, D.E. (1991). Output buffer storage and the modality of recall. *Quarterly Journal of Experimental Psychology, 43A,* 1-18.

Teichner, W.H., and Krebs, M.J. (1974). Laws of visual choice reaction time. *Psychological Review, 81,* 75-98.

Thomassen, A.J.W.M. & Van Galen, G.P. (1992). Handwriting as a motor task: Experimentation, modelling, and simulation. In J.J. Summers (Ed.), *Approaches to the Study of Motor Control and Learning* (pp. 113-144). Amsterdam: Elsevier.

Van Galen, G.P. (1991). Handwriting: Issues for a psychomotor theory. *Human Movement Science, 10,* 165-191.

Van Mier, H. & Hulstijn, W. (1993). The effects of motor complexity and practice on initiation time in writing and drawing. *Acta Psychologica, 84,* 231-251.

Verwey, W.B. (1992). *Effects of practice in selecting and executing keypressing sequences* (Report IZF 1992 B-10). Soesterberg, The Netherlands: TNO Institute for Perception[2].

Verwey, W.B. (1994a). Evidence for the development of concurrent processing in a sequential keypressing task. *Acta Psychologica, 85,* 245-262.

Verwey, W.B. (1994b). *Mechanisms of skill in sequential motor behavior.* Thesis. Soesterberg: TNO Human Factors Research Institute.

---

[2] On January 1, 1994 the name "TNO Institute for Perception" has been changed to "TNO Human Factors Research Institute".

Verwey, W.B. (1995). A forthcoming keypress can be selected while earlier ones are executed. *Journal of Motor Behavior, 3,* 275-284.

Verwey, W.B. (1996). Buffer loading and chunking in sequential keypressing. *Journal of Experimental Psychology: Human Perception and Performance.*

Verwey, W.B. (in prep.) On-line driver workload estimation: Towards an adaptive human machine interface in the car of tomorrow. *Human Factors,* in revision.

Verwey, W.B. & Dronkert, Y. (1996). Practicing a structured continuous keypressing task: motor chunking or rhythm consolidation? *Journal of Motor Behavior, 28,* 71-79.

Wann, J.P & Nimmo-Smith I. (1990). Evidence against relative invariance of timing in handwriting. *Quarterly Journal of Experimental Psychology, 42A,* 105-119.

Welford, A.T. (1976). *Skilled performance: Perceptual and motor skills.* Glenview, IL: Scott, Foresman.

Wickelgren, W.A. (1969). Context-sensitive coding, associative memory, and serial order in (speech) behavior. *Psychological Review, 76,* 1-15.

Willingham, D.B., Nissen, M.J. & Bullemer, P. (1989). On the development of procedural knowledge. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15,* 1047-1060.

Winer, B.J., Brown D.R. & Michels, K.M. (1991). *Statistical Principles in Experimental Design.* New York: McGraw-Hill.

Young, D.E. & Schmidt, R.A. (1990). Units of motor behavior: Modifications with practice and feedback. In M. Jeannerod (Ed.), *Attention and Performance XIII* (pp. 763-795). Hillsdale, NJ: Erlbaum.

Ziessler, M., Hänel, K. & Sachse, D. (1990). The programming of structural properties of movement sequences. *Psychological Research, 52,* 347-358.

Soesterberg, 1 August 1996

Dr. W.B. Verwey
(author, project manager)

REPORT DOCUMENTATION PAGE

1. DEFENCE REPORT NUMBER (MOD-NL) RP 96-0165	2. RECIPIENT'S ACCESSION NUMBER	3. PERFORMING ORGANIZATION REPORT NUMBER TM-96-B011
4. PROJECT/TASK/WORK UNIT NO. 788.2	5. CONTRACT NUMBER B95-008	6. REPORT DATE 1 August 1996
7. NUMBER OF PAGES 45	8. NUMBER OF REFERENCES 92	9. TYPE OF REPORT AND DATES COVERED Final

10. TITLE AND SUBTITLE

Evidence for a multi-stage model of practice in sequential movement tasks

11. AUTHOR(S)

W.B. Verwey

12. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

TNO Human Factors Research Institute
Kampweg 5
3769 DE SOESTERBERG

13. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

TNO Defence Research
Schoemakerstraat 97
2628 VK Delft

14. SUPPLEMENTARY NOTES

15. ABSTRACT (MAXIMUM 200 WORDS, 1044 BYTE)

The purpose of the present study was to explore the effects of practice in a task in which fixed movement patterns are produced. Earlier studies indicated that an encapsulated representation, a motor chunk, develops when a certain movement pattern is repeatedly executed. The motor chunk would be used to control the production of the movement sequence at a processing stage called sequence construction. This would free processing capacity at earlier processing stages and allow for concurrent processing. The present study sought evidence for the sequence construction stage and the notion that the effect of practice at this stage (i.e. motor chunks development) is independent from that at the response selection stage. The reported experiment included a 2500 trial practice phase and four transfer phases including serial response production, stimulus-response reversal, and production of familiar sequences in rapid succession. In the practice phase, independence of response selection and sequence construction was indicated by effects of mapping consistency, foreperiod duration, and sequence length. The transfer phases showed further evidence for independent effects of practice at response selection and sequence construction as well as for concurrent processing.

16. DESCRIPTORS	IDENTIFIERS
Movement Sequences Practice Reaction Time	

17a. SECURITY CLASSIFICATION (OF REPORT)	17b. SECURITY CLASSIFICATION (OF PAGE)	17c. SECURITY CLASSIFICATION (OF ABSTRACT)
18. DISTRIBUTION/AVAILABILITY STATEMENT Unlimited availability		17d. SECURITY CLASSIFICATION (OF TITLES)

VERZENDLIJST

1. Directeur M&P DO

2. Directie Wetenschappelijk Onderzoek en Ontwikkeling Defensie

3. {   Hoofd Wetenschappelijk Onderzoek KL

    Plv. Hoofd Wetenschappelijk Onderzoek KL

4. Hoofd Wetenschappelijk Onderzoek KLu

5. {   Hoofd Wetenschappelijk Onderzoek KM

    Plv. Hoofd Wetenschappelijk Onderzoek KM

6, 7 en 8. Bibliotheek KMA, Breda

Extra exemplaren van dit rapport kunnen worden aangevraagd door tussenkomst van de HWOs of de DWOO.